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General Document 37

AIRCRAFT ACCIDENT INVESTIGATION AT ARL
THE FIRST 50 YEARS

by

J.L. KEPERT

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SUMMARY

Early Australian experience with the investigation of aircraft accidents is covered briefly as a prelude to the foundation of the Aeronautical Research Laboratory. With its foundation, a more scientific approach was possible. ARL was quickly involved with accident investigation, an activity which has been maintained throughout its fifty year history. This report examines ARL experiences during those fifty years with the idea of providing some useful guidelines for the next half-century.

DSTO AUSTRALIA

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1. INTRODUCTION

Flying and accidents seem to be indivisible as Icarus and Daedalus discovered when they attempted to escape the wrath of King Minos by flying from Crete to Sicily on waxed wings. According to the official accident investigation report, Icarus flew too close to the sun, the wax melted, and Icarus ended up in the sea. Some fishermen, discovering feathers floating on the surface and identifying these as ex - Icarus, called the area the Icarian Sea, by which name it is known to this day.

We now know that the altitude rating of waxed wings is far too low for the accident investigation report to be tenable. Further, a wreckage trajectory analysis based on the prevailing meteorological conditions and the terminal velocity of waxed feathers, indicates that the recovered feathers could not have come from the wings of Icarus. In consequence, the Icarian Sea has a position error of some 50 nautical miles.

The saga of Icarus and Daedalus established many traditions including the tradition of aircraft accident investigators to get things wrong. When ARL was founded in 1939, one of its tasks was to break with this tradition. This report examines ARL's experiences in this endeavour during its first fifty odd years in the hope that these experiences will serve as a useful guide for the future.

2. EARLY AUSTRALIAN EXPERIENCES

The first recorded attempt at flight in Australia also ended disastrously. On 15 December 1856, Pierre Maigre attempted to ascend from the Sydney Domain in his hot air balloon; a rope tangled and the attempt ended in a considerable bonfire which consumed balloon, support poles, spectator seats and M. Maigre's hat. In defiance of Icarian precedent, Sydney Harbour was not renamed.

The flying career of another early Australian balloonist, Henri L'Estrange, ended somewhat more dramatically on 15 March 1881 when his gas-filled balloon collided with the top of a house in Woolloomooloo. L'Estrange quickly made his way to the nearest public house just before the balloon exploded casting "a brief but vivid illumination over the entire suburb". A nearby drapers shop caught fire and L'Estrange, who had already achieved historical fame by making the first emergency parachute jump in Australia, decided to give up flying.

Early Australian attempts at powered flight fared little better. The first was when Colin Defries tried to coax a Wright Flyer into the air at Victoria Park Racecourse, Sydney on 4 December 1909. The attempt terminated abruptly when the aircraft struck logs hidden by the long grass. As aircraft became more numerous, and accidents more frequent, the techniques of accident investigation became more sophisticated. Meteorological phenomena were now recognised as an important factor and many accidents were ascribed to "a lack of lift in the air". There was no formal system for the investigation of aircraft accidents and these were left to the discretion of the pilot or the owner or to some other, generally inexpert, body. The nett result was a wide variation in approach.

When John Duigan damaged his first aeroplane at Mia Mia, Vic. during September 1910, he correctly ascribed the accident to a loss of lateral control at low altitude. He promptly modified the design by replacing the rather ineffective interplane ailerons with conventional trailing edge ailerons and the trouble never recurred.

Duigan's second aircraft was basically an Avro Type D fitted with a 35 HP ENV engine. It was built at Ivanhoe, Vic. and then moved to Keilor in readiness for flight testing. On 17 February 1913, its first flight ended when a wind gust produced a rate of roll beyond the capacity of the lateral control system to correct. One wing tip touched the ground, the aircraft cartwheeled and was extensively damaged. Again Duigan correctly identified the fault, viz. the inadequacy of the wing warping system used, and wisely decided against rebuilding. The wreckage was sold to M. Paul Auriac who rebuilt it, subsequently making two or three short flights at Geelong. Its brief career ended in "a fall" into Wighton's Paddock during May 1914 according to the report of the local police.

This casual attitude to aircraft accident investigation was not confined to the Victoria Police. Basil Watson built a biplane resembling a Sopwith Pup at his home in Brighton, Vic. during 1916. Fitted with a 50 HP Gnome rotary engine, the aircraft proved quite successful and made numerous flights. On 28 March 1917, while performing loops over the army camp at Laverton, the port wing collapsed and the aircraft crashed into the sea killing Watson. The cause of the structural failure was never established, or even investigated, by the Australian Army. Immediately before its last flight, the covering of Egyptian cotton had been replaced by Assam silk, but whether this was a contributing factor will forever remain a mystery.

When a Sopwith Gnu of the Larkin-Sopwith Aviation Co. clipped a telephone wire with its tail and crashed while attempting to land at Mornington, Vic. on 2 January 1920, the sole passenger received fatal injuries. The coroner's report is worth quoting in full.

"An Inquisition for our Sovereign Lord King George V, taken at the morgue, Melbourne, in the State of Victoria, the 26th day of March A.D. 1920 in the tenth year of the reign of our said Lord King, by me, Alexander Phillips, gentleman, a Deputy Coroner of our Lord the King for the said State, upon the view of the body of Phillip Roffe Nunn then and there lying dead.

Having enquired upon the part of our Lord the King, when, where, how and by what means the said Phillip Roffe Nunn came by his death, I say that on the 4th day of January 1920 at Mornington Phillip Roffe Nunn died from injuries caused by the accidental overturning of an aeroplane in which he was riding on the 2nd January 1920".

As an insight into the cause of the accident, this leaves something to be desired.

The Mornington accident strongly influenced public perceptions that unregulated flying was no longer acceptable. In a flurry of activity, the Federal Government formed the Air Council and the Air Board with appointments gazetted on 12 November 1920. Supporting legislation was embodied in the Air Navigation Act 1920 and passed on 2 December. The Civil Aviation Branch of the Defence Department was formed with regulations coming into effect on 28 March 1921 and into law three months later. Finally, the Royal Australian Air Force was created out of several defence elements and attained formal existence on 31 March 1921.

One effect of these new arrangements was a marked improvement in the standard of aircraft accident investigations. This was not long delayed since the first accident to be investigated under the new arrangements, that to an Avro 504K flown by F/L Fryer-Smith at Laverton, Vic. occurred on 6 April 1921. The fifth accident to be investigated also involved an Avro 504K, one operated by the Shaw-Ross Engineering and Aviation Co.

On 22 May 1921, Lt H.G. Ross took off from Port Melbourne in the Avro on a joy-flight with two passengers, Cyril Harris and Jessica Dorman. When heading towards the bay, the aircraft suddenly fell into a spin and crashed into the yard of a cottage. There were no survivors. At the inquest, the CAB's Superintendent of Aerodromes, Capt E.C. Johnston, reported that he had examined the wreckage after the accident and found no fault with the machine or engine but that the heel of one of Miss Dorman's shoes had been almost wrenched off. "I am of the opinion that the accident was due to the unfortunate jamming of the heel of Miss Dorman's shoe, thereby rendering the rudder control useless and causing the machine to dive to the ground" he explained.

This simple explanation may well have been true. Certainly it represented a marked improvement over earlier practice. The trouble was that aeroplanes were becoming more complex, even if shoes weren't.

3. THE AAIC

During the 1920's, there was growing public disquiet at what was seen, probably correctly, as officialdom's rather elementary approach to the investigation of aircraft accidents. Events came to a head in 1927 when two accidents occurred before large crowds and, more importantly in the eyes of the daily papers, before the Duke and Duchess of York.

Their Royal Highnesses were visiting Australia to open the new Parliament House in Canberra with due Imperial pomp and ceremony. On 21 April 1927, during their official visit to Melbourne and just as the royal procession was turning from St Kilda Road into the grounds of Government House, two DH.9 aircraft of the RAAF flypast collided. The crowd of many thousands watched as A6-5 and A6-26 disintegrated and plummeted to earth in the vicinity of Sturt Street, South Melbourne. Fortunately, there were no casualties among the crowd but all four RAAF aircrew were killed making it the worst aircraft accident in Australia to that time.

Three weeks later, Their Royal Highnesses had the misfortune to witness the crash of SE-5a A2-24 during the opening ceremony in Canberra on 9 May 1927. The pilot F/O F.C. Ewen was killed. The following day, while returning from Canberra to Melbourne with photographs of the opening ceremony, SE-5a A2-11 suffered an engine failure and crashed in remote bushland near Whitfield, Vic. The pilot, Sgt Orm Denny, walked 25 miles to secure assistance.

This was too much for the newspapers. Bowing to the pressure, Sir William Glasgow, Minister for Defence, signed a Statutory Rule on 25 May 1927 under the Air Navigation Act of 1920 appointing an Air Accidents Investigation Committee. The committee was empowered to make an independent inquiry into aircraft accidents, to study probable causes and to suggest preventative measures.
Composition of the committee was:

- Professor Henry Payne, Melbourne University (Chairman)
- Mr Marcus Bell, Superintendent Defence Laboratories
- Colonel H.B.L. Gipps, Chief Inspector Munitions Inspection Branch
- Squadron Leader Eric Harrison, RAAF
- Captain E.J. Jones, Superintendent Flying Operations, CAB
- Flight Lieutenant William Palstra, RAAF (Secretary)

While some of these men had some previous experience in aircraft accident investigation, the relevance of others is doubtful and the NSW Section of the Australian Aero Club was quick to voice its disapproval.

The committee made a flying start by holding its first meeting at Victoria Barracks, Melbourne on 25 May. AAIC Report no. 1 covered the accident to DH.9C G-AUED at Tambo, Qld on 24 March 1927. This was the first fatal accident suffered by Qantas; the aircraft stalled on final approach and its three occupants were killed on impact. Then followed Reports 2-4 covering the DH.9 collision, A2-24 and A2-11 respectively.

The committee plied its trade with considerable diligence to the extent that when the DH Moth A7-10 crashed at Point Cook, Vic. on 5 January 1930, the matter was addressed by AAIC Report no. 70. On 1 February 1931, membership was reduced from six to three as a government economy measure but the diligence, if not the intelligence, remained unimpaired. Thereafter, the committee seems to have run into an increasing amount of trouble, particularly when investigating accidents which could not be summarised simply as engine failure or pilot error. Accidents to the Jones Wonga VH-ULZ and the Puss Moth VH-UPM in 1932 produced a crisis.

The Wonga was a single engine, high wing monoplane designed by L.J.R. Jones and built during 1929-30. After successfully completing about 100 hours of flying, the aircraft crashed during a short test flight at Quaker's Hill, NSW on 16 June 1932. Eyewitnesses observed the aircraft to bank steeply before diving to the ground causing fatal injuries to both occupants. At the inquest held on 5 July 1932, the AAIC reported its conclusion that the accident had resulted from low flying and bad weather. Subsequently T.D.J. Leech, lecturer in civil engineering, University of Sydney, built a scale model of the Quaker's Hill area and tested it in the G.A. Taylor memorial wind tunnel. From these tests he concluded that the aircraft probably encountered severe turbulence when the loss of control occurred.

These findings, together with the unhappy experience of the Puss Moth described in the next section, promoted a crisis of confidence in the AAIC. In a report to the Federal Government, a voluntary committee of aeronautical engineers charged the AAIC with insufficient inquiry, faulty conclusions and unfair reflections on the ability of deceased pilots. It recommended that all of the personnel of the AAIC be replaced with experts drawn from appropriate professional and scientific fields. Faced with open rebellion, the government predictably closed ranks. On 21 April 1933, Sir George Pearce, Minister for Defence, stated that "the voluntary committee had adopted an attitude of superiority which neither the constitution or qualifications justify" and the AAIC lived to fight another day.

4. THE PUSS MOTH ACCIDENTS

The Puss Moth accidents are notable for four reasons; they were international in character, they resulted in the death of some famous Australian airmen, they promoted the application of scientific research to aircraft accident investigation, and they contributed, however subconsciously, to the establishment of ARL. They are worthy of closer examination.

The Puss Moth was a conventional high wing cabin monoplane with vee strut bracing. Designed by De Havillands as the DH. 80A, it proved highly successful; two hundred and sixty were built in the UK and a further twenty five were assembled in Canada. However, its early history was marred by a rash of accidents involving in-flight structural failure:

- 13.10.30 VH-UPC Darling Ranges near Perth, WA
- 5. 5.31 ZS-ACC Van Reenen, South Africa
- 13.11.31 ZS-ACD Sir Lowry's Pass, South Africa
- 21. 5.32 G-CYUT Ottawa, Canada
- 27. 7.32 G-ABDH Churt, Surrey, UK
- 18. 9.32 VH-UPM nr Byron Bay NSW
- 29.10.32 G-ABJU Grenoble, France
- 7. 1.33 CF-APK Tuscan Mountains, Italy
- 22. 6.33 HS-PAA between Khonkaen and Udorn, Siam

Captain C.H.F. Nesbit, with two students, was killed in the crash of VH-UPC. Nesbit had previously flown with West Australian Airways before joining C.W. Snook to form Wings Ltd. This company formally registered VH-UPC just six days before it crashed. Captain L.H. Holden died in VH-UPM with Ralph Virtue. Following a distinguished war record (MC,AFC) with no. 2 Squadron Australian Flying Corps, Holden made a career in civil aviation. While flying his DH.61 *Canberra*, he located the missing *Southern Cross* in the "Coffee Royal" affair. Among his crew on that occasion was Dr G.R. Hamilton, joint owner of the *Canberra* who also died in VH-UPM.

The crash of CF-APK ended the career of H.J. Hinkler. About Bert Hinkler, little need be said. The Puss Moth had faithfully carried him solo from New York to Venezuela, across the South Atlantic in 22 hours to Africa, then to the UK before finally letting him down while en-route to Australia. Whatever the problem with the aircraft, it showed no respect either to skill or experience.

Once the problem was recognised, the Aeronautical Research Committee set up an Accident Investigation Sub-committee with Sir R.T. Glazebrook as chairman. Among its distinguished company was H.E. Wimperis, Director of Scientific Research, Air Ministry, who later reported on the inauguration of aeronautical research in Australia at the invitation of the Federal Government. On his recommendation, the government established the Aeronautical Research Laboratory in Melbourne and a Chair of Aeronautics at Sydney University.

Investigations by local authorities had shown that, in all cases, the accident had resulted from the in-flight failure of one or both wings. Accordingly, the sub-committee began by investigating the static strength of the aeroplane. Tests by the manufacturer showed that

it easily met the load factor requirements of +5.5g and -2.75g specified for the normal category when the type certificate was issued in May 1930. Additional tests carried out by the RAE Farnborough supported this conclusion but indicated the desirability of fitting a stabilising bar to the forward leg of the vee strut; see Fig. 1. This mod was incorporated on 21 March 1932.

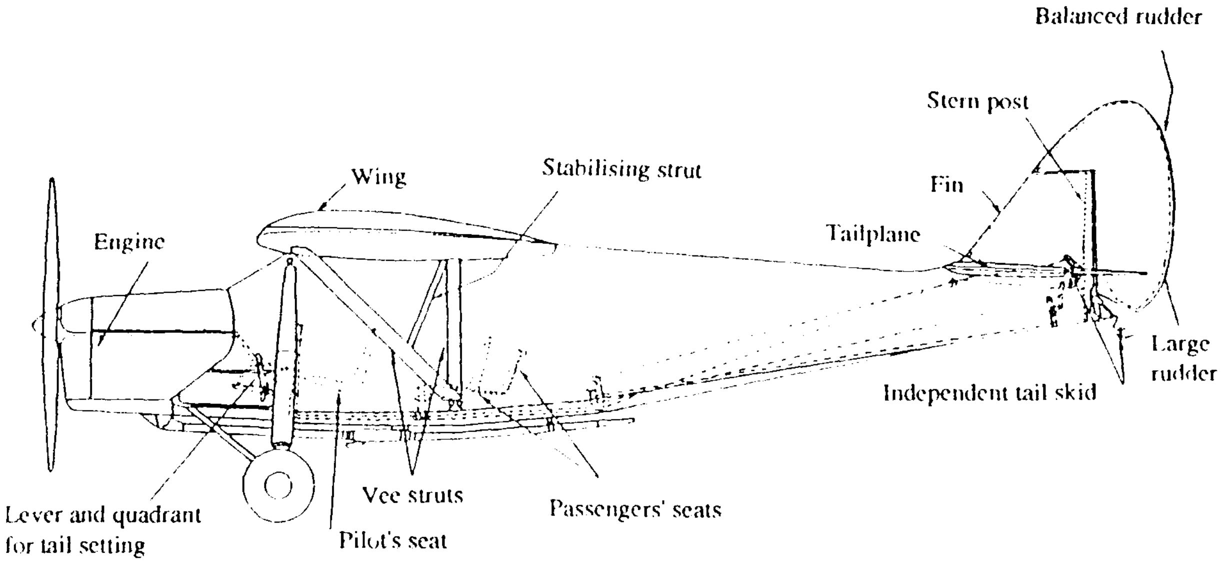


Fig. 1 **DH Puss Moth showing location of stabilising strut**

Some early occurrences of rudder flutter had been experienced in Canada. While these were not catastrophic, the fitting of rudder mass balances was directed by a mod dated 28 November 1932. However, the last two accidents were to aircraft incorporating this mod, and their wreckage showed no evidence of in-flight failures in the tail unit. Most significantly, the Australian report on VH-UPM was adamant that its tail surfaces, not mass balanced, were intact at ground impact and not a factor in the accident. This evidence, with the results from wind tunnel tests on a quarter scale flutter model of the Puss Moth rear fuselage and tail unit, led the sub-committee to reject rudder flutter as an adequate explanation of the accidents.

The wreckage from most of the accidents, including VH-UPM, was collected together in the UK and examined by the Inspector of Accidents. He observed that the wings all exhibited similar features. The spars were broken in several places, portions of each wing tip were missing, all the outer ribs were missing or badly shattered, the outer drag struts were broken and had pushed through either the front or rear spar. To the sub-committee, these features suggested that an appreciable fore and aft component of alternating strain, i.e. racking motion, had contributed to the wing failures. This, in turn, suggested the possibility of wing-aileron flutter particularly since the vee strut "contributes less torsional stiffness to the wing than would have been the case with the (then) more usual four point attachment to the fuselage."

Wind tunnel tests on a quarter scale model of the wing showed a critical flutter speed of 170 mph for the antisymmetric bending mode with zero backlash in the aileron control circuit. With backlash present, the critical speed was somewhat lower, and further

reduced when the fuselage attachments were allowed some freedom of movement. The mode exited contained a significant fore and aft component. This led the sub-committee to conclude that wing-aileron flutter was the most probable cause of the accidents. ARC Reports and Memoranda No. 1645, Report on Puss Moth Accidents, concluded "The sub-committee is strongly of the opinion that routine calculations or experiments on flexibility should be made for each design so as to cover the possibilities of failure due to the interaction of structural distortion and aerodynamic loadings".

This was a strong endorsement of the view, always held by the AAIC, that the accident to VH-UPC resulted from wing flutter. It had recommended the fitting of aileron mass balances three years before the sub-committee's report and the last seven accidents occurred to aircraft so modified. In its report on the accident to VH-UPM, the AAIC also drew attention to the fact that one aileron balance weight was missing from the wreckage and could not be located; in itself, highly suggestive of flutter. Following the sub-committee's report, improved aileron mass balances were fitted and the problem never recurred. The DH.85 Leopard Moth, successor to the Puss Moth, always featured prominent aileron mass balances; De Havillands didn't make the same mistake twice.

The Puss Moth accidents led to the first mathematical analysis of flutter reported in the now-famous ARC R & M 1699 Report on Puss Moth Accidents by R.A. Frazer, W.J. Duncan and A. R. Collar. This report is highly regarded as initiating scientific research into flutter. Flutter had of course occurred in earlier aircraft but had not been recognised as such. For example, it is highly probable that the wing failures which plagued the Albatros D.III, and more particularly the D.Va, arose from flutter. It is significant that the problem only arose when the parallel interplane struts of the earlier D.I and D.II were superseded by the vee struts of the later models.

In retrospect, it is clear that the AAIC performed commendably in the Puss Moth accidents. Its accident reports were detailed and accurate, it correctly diagnosed the problem at an early stage, and it recommended a possible solution. It could do no more since it lacked the necessary support facilities such as those made available to the Accident Investigation Sub-committee by RAE Farnborough. However, the AAIC performed less well in the DH.86 accidents.

5. THE DH.86 ACCIDENTS

As Qantas prepared to inaugurate Australia's first regular overseas air service, the airline issued a requirement for a light airliner with four engines to provide engine-out reliability for the long crossing of the Timor Sea. De Havillands responded by designing the DH.86 to the Qantas requirement. Holyman's Airways also saw the DH.86 as suitable for regular services across Bass Strait and ordered four. The first, VH-URN *Miss Hobart* was shipped to Australia in September 1934 and made its first Bass Strait crossing on 1 October 1934.

On 19 October 1934, VH-URN disappeared somewhere off Wilson's Promontory, Vic. with the loss of Captain V.C. Holyman, the co-pilot and nine passengers. An aircraft seat, found washed up on the beach at Waratah Bay, was the only trace of the aircraft ever found. In its interim report to Mr R.A. Parkhill, Minister for Defence, the AAIC was unable to give any cause for the accident.

The first Qantas aircraft , VH-USC, was flown out from England arriving in Brisbane on 13 October 1934. The second, VH-USG under the command of Captain Prendergast, was also flown out reaching Longreach on 14 November 1934. Early next morning, the aircraft took off from Longreach on the last leg of its delivery flight to Brisbane. As it climbed away, two eyewitnesses observed the aircraft to enter a flat right hand turn which quickly developed into a flat right hand spin as forward speed was lost. This spin was maintained until the aircraft struck the ground in a slightly nose down attitude killing all four occupants. All DH.86's were withdrawn from service pending an investigation.

At the request of the AAIC, Qantas made a series of test flights on VH-USC which revealed nothing unusual. Additional structural strength tests carried out by the manufacturers at Hatfield revealed no obvious structural weakness. However, two modifications were introduced as a precautionary measure. As originally designed, the DH.86 achieved rudder control through a servo tab and the flight tests showed that this could be excessively powerful if misused. Accordingly, the servo tab was removed and replaced by a conventional rudder control system.

The DH.86 achieved directional trim by a transverse screw jack which engaged with a mating fitting at the front of the fin. Operation of the jack applied a bias to the fin thus obtaining the desired trim. This mating fitting also transferred the fin and rudder drag loads to the fuselage via the screw jack. An examination of the wreckage showed that both the fin post and the mating fitting had failed, Fig. 2. Again as a precautionary measure, the front fin attachment fitting was strengthened. On 5 December 1934, the AAIC reported to Mr Parkhill. "Evidence has disclosed a weakness in the front fin attachment point but the Committee --- is of the opinion that the fin did not carry away in the air --- insufficient evidence to establish definitely the cause of this accident --- also in view of the fact that no further wreckage of *Miss Hobart* had been found, the interim report was considered final".

Fig. 2 Tail unit of DH.86 VH-USG following its accident at Longreach

While opinions are still divided on the cause of this accident with directional instability, incorrect loading and, of course, pilot error having their advocates, the sequence of events may be established from Fig. 2.

a. The front fin attachment failed. Deprived of fore-and-aft support, the fin post failed in rearwards bending under the applied drag loading. (If the fin post had failed at ground impact, it would have tilted forwards not rearwards.)

b. The rearwards tilting of the fin post disengaged the mating fitting from the screw jack allowing the fin to rotate about its hinges until it contacted the starboard bracing wire. (The absence of scratch markings on the upper surface of the starboard tailplane indicates that failure of the fin post preceded rotation of the fin.)

c. The starboard bracing wire pulled away from the tailplane rear spar tearing a hole in the upper surface of the tailplane. All damage must have a cause and the existence of this hole cannot be explained in any other way. (Ground impact would have applied compressive loads to the starboard bracing wire, not tension, as evidenced by the ground impact damage to the tip of the starboard tailplane.)

d. As the fin rotated to starboard, it pulled the port servo tab control cable around the fin post thus deflecting the tab to port through an abnormally large angle. This, in turn, forced the rudder to starboard. (The intact control cable and the extreme position of the tab are clearly shown in Fig. 2.).

e. With hard right rudder applied, the aircraft began turning to the right. Because of the high drag and downwards load applied by the rotated and tilted fin, this quickly developed into a flat right hand spin from which recovery was impossible.

Thus the evidence of the wreckage is fully consistent with the eyewitness reports. Collectively, they indicate that the accident was caused by failure of the front fin attachment. It is interesting to observe that VH-URN and VH-USG must each have flown about 12,000 miles by the time of their respective accidents. This suggests the possibility of fatigue but whether the front fin attachment of VH-USG contained any fatigue cracks will forever remain unknown.

This was not quite the end of the DH.86 story. On 2 October 1935, Holyman's VH-URT *Loina* crashed into the sea some two miles off Flinders Island after making a radio call that it was about to land. There were no survivors from the five on board. Again an exhaustive program of flight tests, this time using Holyman's VH-USW *Lepena*, failed to disclose any shortcomings and, again, the AAIC report was unable to give any apparent cause for the accident. Then came *Lepena's* turn.

On 13 December 1935, *Lepena* was crossing Bass Strait when the pilot, Captain A. Bayne, noticed that a wing fitting was loose. Understandably alarmed, he elected to make an immediate forced landing on Hunter Island with some damage to the aircraft but none to its occupants. Certificates of Airworthiness of DH.86 aircraft were immediately withdrawn, an action which generated a storm of criticism from England as being hasty and ill-considered. The certificates were reinstated on 15 December when an

fairing, of no structural significance, which had worked loose allowing it to slide up and down on the strut.

The DH.86 went on to give long and honourable service to the Australian airline industry but its first year revealed some shortcomings, including those of the AAIC. The next crisis occurred in 1937 when a series of accidents to Hawker Demon aircraft brought the AAIC, once again, into the public eye.

6. THE DEMON AND ANSON ACCIDENTS

In the late 1930's, the RAAF entered a period of rapid expansion which was to last until the end of WW.2. Inevitably this created many problems, one of which was a dramatic increase in the accident rate. The drama opened when Demons A1-3 and A1-8 became lost in bad weather over Northern Tasmania on 3 February 1937; see AAIC Report 173. Both made forced landings and A1-8 was subsequently abandoned in thick bush near Wynyard as being beyond economic salvage. (Ironically, it was recovered in 1977, restored and placed in the Point Cook Museum as the RAAF's last surviving Demon). Next to go was A1-40 which suffered a structural failure of its port wing while performing aerobatics over Townsville, Qld on 14 May. AAIC Report 176B blamed the pilot for overstressing the aircraft, surely a virtual impossibility in a properly maintained Hawker Demon. Then on 31 August, A1-32 stalled just after taking off from Hamilton, Vic. and both crew members were killed; AAIC Report 182A.

A climax was reached in November - December when nine Demons embarked on a flight from Laverton to Brisbane as a training exercise. The exercise produced seven separate accidents or incidents which, with two others, gave nine for a three-week period. Most of these were relatively minor but Demons were destroyed as follows:

- A1-33 Frampton near Cootamundra, NSW, 5 December 1937
- A1-36 Cootamundra, NSW, 6 December 1937
- A1-10 Avoca Bridge near Gosford, NSW, 7 December 1937

With six aircraft destroyed, and with four aircrew killed, 1937 was not a good year for the Demon. Again the Minister for Defence, Mr H.V.C. Thorby, called for a report (AAIC Report 184) with, again, a predictable response from the English press.

In its edition of 5 June 1938, *The Aeroplane* was particularly scathing. "---the inquiry is typical of the Australian government which goes into a panic because fitters do not adjust the brakes and because inexperienced pilots slew their machines into one another.--- At least three of the mishaps were caused by faulty brake adjustment, one due to bad pilotage and the rest to the inability to make a forced landing successfully, so only Australia and Ruritania institute an inquiry." Undeterred, the AAIC reviewed 1937 stating that of the 96 accidents investigated, 67 were due to pilot error, 28 due to various other causes and in only one had it been unable to establish a cause; a highly creditable performance by the AAIC, at least in its own eyes.

The drama of the Demon continued into 1938 when A1-51 collided with a tree during a mock dog-fight at Llandillo, NSW on 14 June. On 20 July, A1-29 suffered an engine failure and was written off in the attempted forced landing at Douglas Park, NSW, while A1-45 stalled while attempting a steep turn immediately after take-off from Pearce, WA on 16 September. However, 1938 really belonged to the Avro Anson with serious accidents as follows:

- A4-27 Green Hills near Liverpool, NSW, 29 May 1938, side-slipped into ground while turning - 3 killed
- A4-29 Arthur's Seat, Vic, 10 August 1938, collided with hill in dense fog - 4 killed
- A4-36 Whitfield, Vic, 15 August 1938, encountered icing - major damage in forced landing
- A4-35 Point Cook, Vic, 5 September 1938, collided with tree during night landing
- A4-15 Currie, King Island, Tas, 11 September 1938, burnt out following a forced landing
- A4-8 Windsor, NSW, 16 October 1938, structural failure of starboard wing.

Most of these accidents could be attributed to pilot error and adverse weather, particularly since these early Ansons were not fitted with blind-flying instrument panels. However, the accident to A4-8 was not so simple and the AAIC concluded that the wing had apparently exploded in flight.

The final straw was provided by a civil aircraft, viz. Douglas DC-2 VH-UYC *Kyeema* of Australian National Airways. On 25 October 1938 while completing a flight from Adelaide to Melbourne, *Kyeema* overshot Essendon in dirty weather conditions and collided with the crest of Mt Dandenong. All 18 aboard were killed making this by far the worst aircraft accident experienced in Australia to that time. The resultant public inquiry provided a forum for a general airing of grievances including newspaper allegations that the AAIC had gagged the press by refusing to allow publication of evidence of defects in Anson aircraft. The government reacted promptly; the Civil Aviation Branch was abolished and the creation of a Department of Civil Aviation received formal approval on 5 December 1938. Seven days later, Mr Thorby announced the government's intention to establish a permanent Air Court of Inquiry.

On 28 April 1939, Anson A4-32 crashed at Riverstone, NSW after both engines failed in flight, probably through mismanagement of the fuel system. Then on 2 May 1939, Anson A4-11 crashed into Port Phillip Bay off St Kilda while descending through fog. There were no survivors from either accident. Press photographers at the Riverstone crash site were manhandled by RAAF guards which produced another furore and an apology from the Minister for Defence, now Mr G.A. Street. On 5 May, the Prime minister, Mr R.G. Menzies attempted to smooth ruffled feathers by restating the government's intention to establish a permanent Court of Inquiry. Whatever the intention, nothing eventuated.

From mid 1939, the RAAF assumed authority for the investigation of accidents to its own aircraft while DCA was responsible for those to civil aircraft. In performing these duties, both bodies were free to utilise the scientific and technical expertise contained within a newly-formed aeronautical research establishment. Amid all these changes, the AAIC seems to have died a natural death. Its report on the accident to Anson A4-27 was issued on 18 May 1939, i.e. almost one year after the accident, giving no specific cause. Remaining outstanding reports were completed and the AAIC finally disappeared some time during 1940.

7. ARL AND THE ANSON WING

As stated previously, the recommendations of the Wimperis report led to the establishment of the Aeronautical Laboratory, Division of Aeronautics, CSIR, in April 1939. Among the many points made by Wimperis in his comprehensive report was that the failure of aircraft components in service would need to be addressed in Australia and without delay. In making this point, Wimperis was clearly aware that Australia could not always rely on the unqualified support of the relevant overseas design authority. In respect to his comment on delay, it is likely that Wimperis was mindful of the Puss Moth experience where 18 months elapsed between the first accident (in Australia) and its referral to the Accident Investigation Sub-committee.

Since its founding, ARL has passed through a number of organisational changes to achieve its present position as the Aeronautical Research Laboratory, Defence Science and Technology Organisation, Department of Defence. With advances in technology, many of its functions have changed but one function, that of providing scientific and technical support to the investigation of aircraft accidents, remains unchanged.

This feature is indicated by Appendix 1 which gives a listing of ARL publications concerned with accident investigation. In the following sections, some of these investigations are discussed under causal headings. No particular format is followed but emphasis is given to those investigations which had a significant consequence. The first of these was provided by the faithful Avro Anson.

Whenever an aircraft wing fails in flight, there is never any real doubt as to what happened; the detached wing section is always to be found well separated from the main body of the wreckage. The important question is why did the wing fail? Frequently, the answer to that question generates considerable follow-up action.

Anson A4-5 crashed at Glenbrook, NSW on 29 January 1941 while flying from Parkes to Sydney. It was immediately obvious that the port wing had failed in flight and the detached wing sections were sent to ARL for expert examination. As designed, the one-piece wooden wing of the Anson followed standard Fokker practice. Two box beam spars, internally braced, were built up from laminated booms and plywood webs, and connected by plywood ribs. The whole was then covered by a load-carrying plywood skin locally thickened by cushion strips where it passed over the spar booms.

At ARL many test specimens were cut from the wing sections and subjected to tensile, shear and impact tests. The results obtained were generally satisfactory but specimens cut from the skin-main spar joint showed a shear strength less than half the specified

value. Visual examination of this joint disclosed extensive areas of poor adhesion, delamination and excessive glue thickness. ARL concluded that quality control during manufacture had been poor with insufficient pressure applied to the joint during curing of the casein glue used, S & M Report 6.

It is interesting to compare the ARL conclusion on the port wing of A4-5 with that reached by the AAIC with respect to the starboard wing of A4-8; see Section 6. For the latter, the AAIC concluded that the wing 'apparently exploded' and let it go at that. It is also interesting to note that both aircraft were drawn from the first RAF production batch of 174 aircraft of which K6212 - K6223 were shipped to Australia to become A4-1 to A4-12.

Concurrently with the work on A4-5, ARL carried out similar inspections and tests on the main spar of Anson N1331 which had been damaged in a ground collision. This wing had been manufactured during September 1938 as part of the fifth RAF production batch of 98 aircraft. By this time, modern synthetic resins were replacing casein and N1331 made extensive use of urea formaldehyde (UFD). This work suggested that the strength of UFD deteriorates with age and was one of the first indications of this adverse property.

This early work on Anson wing failures generated a comprehensive program of research. The static strength of Anson wings was investigated in a full-scale structural test, Fig. 3. Improved structural analysis techniques were formulated for wooden box beams while the strength and stiffness characteristics of plywood panels and shells were investigated. The ageing properties of UFD were quantified leading, ultimately, to the final grounding, in Australia, of all aircraft constructed with this resin. The effect on bonding strength of extreme temperature and humidity cycles was examined; work which continues to this day in connection with modern fibre reinforced composite materials.

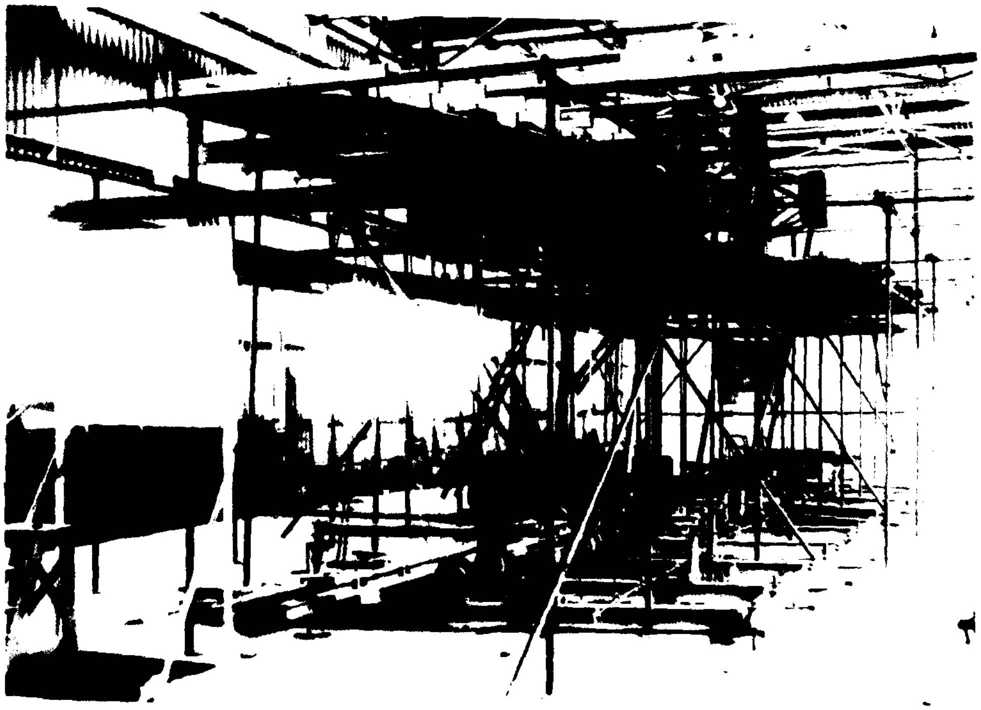


Fig. 3 **Anson wing under test. This was the first full-scale wing test to be carried out by ARL**

This work on wooden wings reached its climax with the De Havilland Mosquito. The Mosquito entered production in Australia as the FB Mk. 40 and the first, A52-1, made its test flight at Bankstown on 23 July 1943. Unfortunately, early production aircraft experienced three catastrophic wing failures as follows:

- A52-12 Bankstown, NSW, 10 June 1944
- A52-18 Bankstown, NSW, 8 November 1944
- A52-29 Williamtown, NSW, 31 January 1945.

There were no survivors from the aircrew involved. Since Mosquito wing failures were relatively common in the UK during World War 2, there were periods when several occurred every month, the Australian experience was not unusual. The Mosquito was a very clean aircraft which accelerated quickly in a dive. Its elevator control was particularly light with low stick forces per g; a combination of design features which made it relatively easy for a pilot, inexperienced on the type, to overstress the aircraft during dive recovery.

Examination of the wreckage of the first two aircraft disclosed no structural deficiencies and these accidents were attributed to pilot error. However, A52-29 disclosed clear evidence of defective glued joints and ARL embarked on a comprehensive program of full-scale structural tests on Australian made Mosquito wings using the techniques developed for the Anson. These tests showed the Australian wing to be satisfactory and, in fact, slightly superior to Mosquito wings built in the UK. It was therefore concluded that the poor quality control evident in A52-29 was an isolated case.

8. THE ROLLING PULL-OUT MANOEUVRE

When aileron is applied to produce a rolling moment, the normal symmetric bending and torsion loads on the wing are augmented or attenuated by the forces and moments generated by the ailerons. The downwards moving aileron increases the bending loads and reduces the nose-up torsion loads while the upwards moving aileron has the opposite effect. If the symmetric loads are high, such as would be generated in a high g pull-out, then the combined loading may be sufficient to cause the wing to fail. Simultaneous application of elevator and aileron is not a standard design case and should be avoided, particularly at high speed when high g loadings are comparatively easy to achieve. If unavoidable, then the pilot needs to be conscious of the fact that the aircraft's placarded g limits are reduced by some, frequently undefined, amount.

Anson A4-5 was not the first accident to be investigated by ARL. That dubious honour belongs to Wirraway A20-201 which suffered an in-flight failure of its port wing a few weeks earlier, S & M Report 5. Since A20-201 was a new aircraft having been delivered as late as the 19 December 1940, the RAAF suspected that faulty manufacture might have been a contributing factor. Accordingly, the detached wing section was sent to ARL for detailed examination. Again, many specimens were cut from the wing section and subjected to proof and ultimate load tests. The results showed a general conformity with specification requirements indicating that materials and workmanship were up to standards. Hence it was necessary to seek some other explanation for the accident.

One obvious feature of the detached wing section was the gross upwards deformation of the leading edge. This had occurred when the leading edge ribs collapsed. On the Wirraway, the leading edge ribs were attached to the stringers via cleats rather than being riveted directly to the skin. While this was indifferent detail design, tests on the cleats showed these to have adequate strength.

Whenever a leading edge is damaged in this way, it is usual to assume that the chordwise pressure distribution is such as to apply excessive aerodynamic loads to it. Wing bending loads are not a contributing factor since, in multi-spar wings, the leading edge is not part of the primary structure. It was therefore concluded that the wing had been twisted leading edge up by an upwards moving aileron. The resultant increase in the angle of attack generated excessive chordwise bending loads on the leading edge causing it to deform upwards as the ribs collapsed. This, in turn, further increased the effective angle of attack and the chordwise bending loads. These, in combination with the symmetric bending loads developed in a rolling pull-out manoeuvre, caused the wing to fail in upwards bending and nose-up torsion.

The validity of this conclusion was strikingly confirmed 17 years later when, on 1 April 1958, Wirraway A20-679 crashed at Werribee, Vic. The aircraft was making a dive-bombing attack on a ground target when, during the subsequent pull-out the port wing failed. Two views of the accident site are shown in Figs 4 and 5.

Fig. 4 **Wreckage trail of A20-679 looking towards the You Yangs in the direction of flight with the impact crater at lower left**

Fig. 5 The burnt out fuselage of A20-679 marked the end of the wreckage trail

Examination of the wreckage revealed that the mode of wing failure was virtually identical with that exhibited by A20-201, Fig. 6. In the later accident, ARL had the benefit of being able to inspect all of the wreckage, not just the detached wing section, Applied Report 6. This confirmed that the starboard wing had incurred no in-flight damage and that the port aileron was up at the moment of wing failure; two features which could only be inferred during the investigation into A20-201.

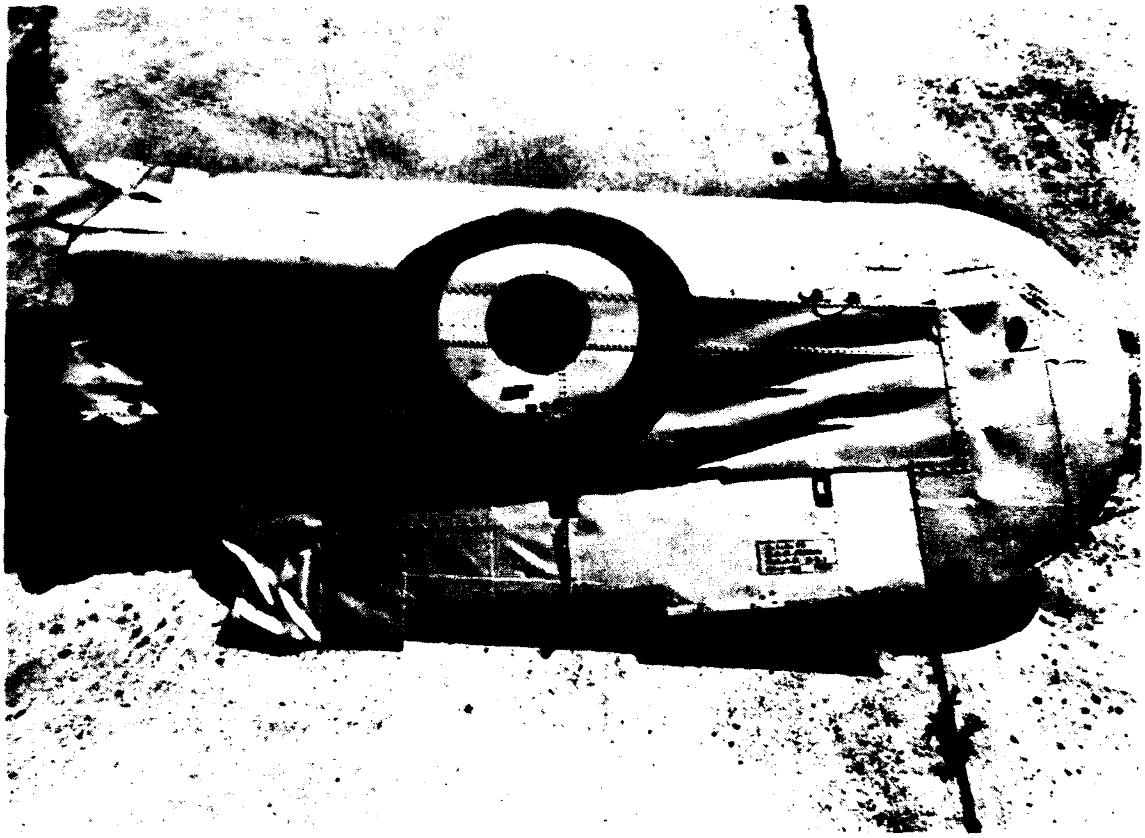


Fig. 6 **Lower surface of the detached port wing from A20-679 showing the upward collapse of the leading edge. The downwards bending failure of the tip occurred under inertia and aerodynamic loading when the wing failed**

The Commonwealth Aircraft Corporation built 757 Wirraways for the RAAF and the aircraft saw long service as a trainer, tactical reconnaissance aircraft, dive-bomber and even fighter. In static strength tests, the wing had successfully withstood the design limit load (DLL) of 5.67 g without damage. Given the diverse usage, it is likely that Wirraways had achieved this load factor on many occasions without trouble. Hence, the two accidents may be seen as isolated cases which, in the event, provided examples of the additional torsion loads produced by an upwards moving aileron. Bristol Freighter A81-2 demonstrated the opposite case, that of the additional bending loads provided by a downwards moving aileron.

On 25 November 1953 near Mallala, SA, A81-2 was observed to be diving at a speed approaching the placard limit speed (V_{NE}). As it pulled out of the dive at an altitude of 4,000 ft, the port wing failed and the aircraft crashed killing the crew of two. An examination of the separated port wing, Fig. 7, showed that the wing had failed in overload bending without the prior leading edge collapse which characterised the Wirraway wing failures. The examination also showed that the port aileron was deflected 10° down when wing failure occurred, S & M Report 224.

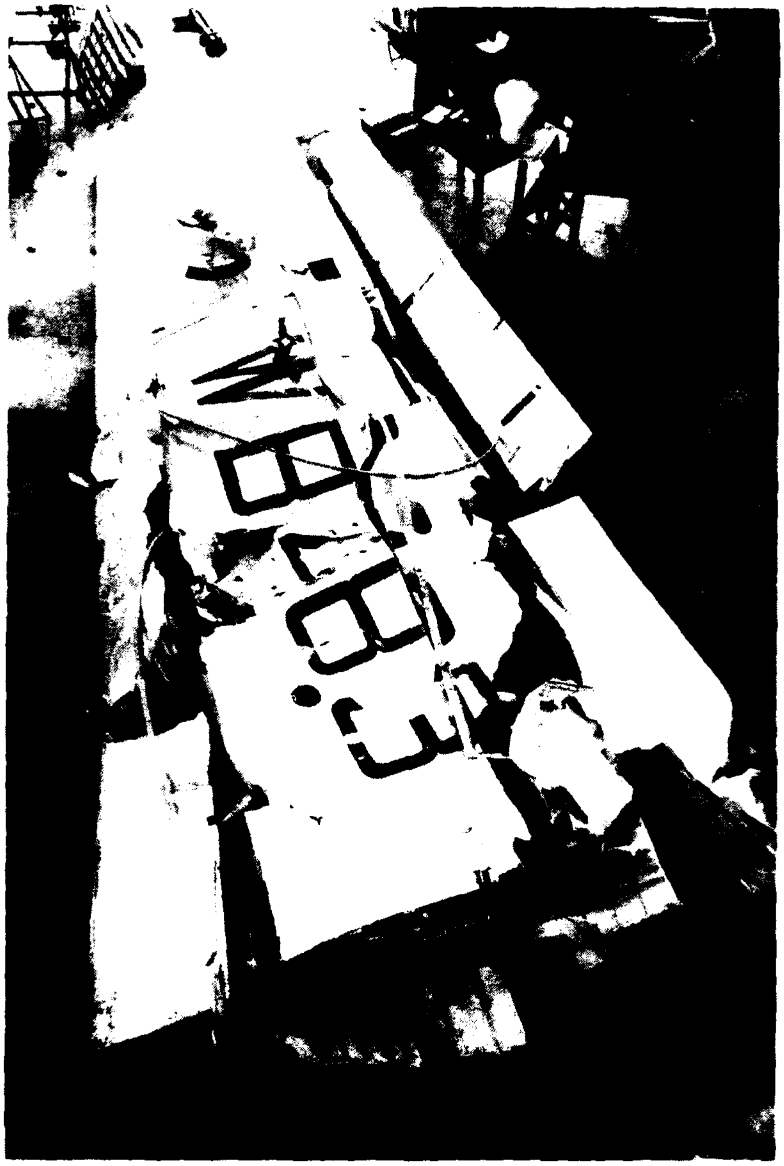


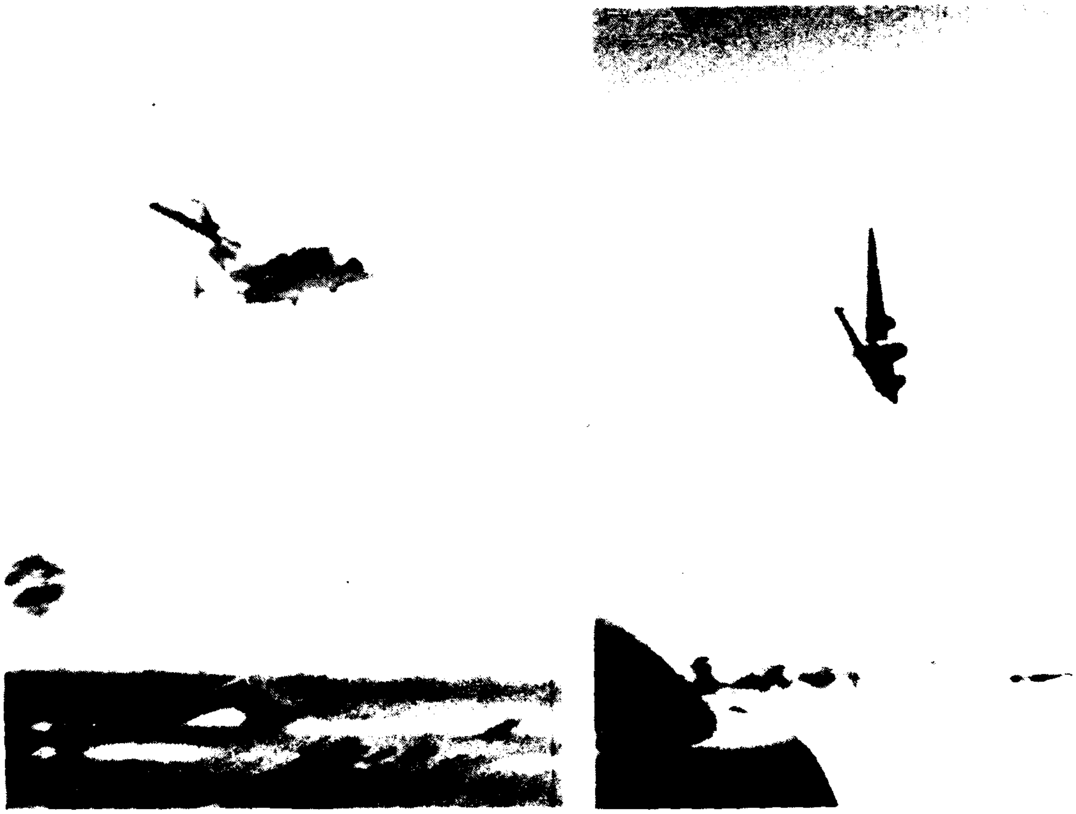
Fig. 7 **Port wing of A81-2 re-assembled to show the mode of failure. The lower surface retained the aircraft's original RAF serial**

The Bristol Freighter was designed in the non-aerobatic category to have a DLL of 3g and a design ultimate load (DUL) of 4.5g. Following the accident to A82-2, ARL re-calculated the strength of the Freighter wing using data obtained from tests on speci nens cut from the detached port wing. This showed the wing to be under strength for the certified all-up weight (AUW) of 40,000 lb. However, at the accident weight of 33,900 lb, the wing would not have failed in symmetric bending at the placard limit load factor of 3g but would have required a little over 3.7g. It seemed unlikely that the latter figure could have been achieved in a symmetric pull-out and ARL concluded that wing failure had occurred in a rolling pull-out manoeuvre; a conclusion supported by the position of the port aileıon.

Two other examples of the rolling pull-out manoeuvre are of interest because of the unusual additional factors involved. The first of these concerns Lockheed Hudson A16-38. Early in 1942, this aircraft had been badly damaged in persistent attacks by Japanese fighters while flying an operational mission over Salamaua, New Guinea. It survived these attacks to make a safe landing at Port Moresby and was then returned to Australia for permanent repairs. On 27 October 1942, A16-38 was detailed to make a low level, high speed flypast for the benefit of a Cinesound Newsreel cameraman at Bairnsdale, Vic. Full power was applied at an altitude of 1,500 ft and the aircraft commenced a shallow dive towards the airfield. As it pulled out at about 70 ft, the starboard wing failed; the pilot, Squadron Leader F.C. Tampion, and his three crew members were all killed.

This is one of the very few occasions in which a wing failure has been filmed as it happened. Some frames from the film are reproduced in Fig. 8. Frame A shows A16-38 commencing to pull out as it crosses the airfield. Frame B shows the instant of failure of the starboard wing. While the leading edge is blurred, the trailing edge is relatively sharp indicating that the wing is twisting, leading edge up, about the trailing edge. Comparison between A and B reveals that the aircraft had just started rolling to port when the wing failed. Frame C shows the starboard wing sections separating from the aircraft as it starts to roll back to starboard. One of these sections struck and damaged the starboard fin and rudder. Frame D shows the aircraft after rolling some 90° to starboard. The violence of the roll is attested by the angular displacement of the tailplane and the extension of the port undercarriage under inertia loading.

Figs. 8A and 8B **A16-38 crossing the Bairnsdale Airfield with the starboard wing failing 0.05 seconds later**



Figs. 8C and 8D **The starboard wing separating and disintegrating 0.1 seconds after frame B with A16-38 then rolling uncontrollably to starboard**

When the starboard wing sections arrived at ARL, it was immediately obvious that the wing failure initiated at the inboard end of a repair which had been carried out on the lower surface leading edge skin between wing stations 168-180. This area is located in the outer wing panel outboard of the wing joint at station 119. The repair was poorly designed in that it terminated in a double staggered row riveted joint using 3/32 in. rivets at one inch pitch. This joint had failed through shearing of the rivets without any associated tearing of the skin edge, Fig. 9. It is most unusual for riveted joints to fail in this way and indicates a gross mismatching between skin tensile strength and rivet shear strength.

Fig. 9 **Starboard wing of A16-38 showing failure details. Forward of the spar, the joint has failed by shearing of the rivets (lower centre) in contrast with the skin tearing evident aft of the spar (upper left)**

The Lockheed Hudson was of single spar design. In this arrangement, the torsion box is formed by the spar and the leading edge so that the leading edge is part of the primary structure. Using test results obtained from specimens cut from the wing sections, S & M Report 17 calculates that the strength of the repair joint was only 55% of DUL. This corresponds to an ultimate failing load of 2.5g assuming a DUL of 4.5g at an AUW of 17,500 lb. The report also notes that there were several bullet holes in the wing which had been repaired satisfactorily.

The aircraft had flown 110 hours since the repairs were made. It is not difficult to imagine that 2.5g would not be exceeded during this time but it is more difficult to imagine a symmetric manoeuvre of this magnitude under the circumstances of the accident. Accordingly, ARL concluded that the accident was caused by a high speed rolling pull-out manoeuvre generating wing bending loads in excess of those which the starboard wing, weakened by a poorly designed repair, could withstand.

The second example in that of CAC Winjeel A85-416. On 3 May 1968, A85-416 was flying above the Bellarine Peninsula near Drysdale, Vic. when the starboard wing failed in flight. An unusual feature of this accident is that the wing failed in three places. The initial and primary failure involved compression buckling of the upper surface skin at station 62, immediately outboard of the wing joint, Fig. 10. As the wing commenced to

rotate upwards about station 62, a second failure occurred further outboard at station 180 in downwards bending and torsion under the combined action of the high inertia and aerodynamic loads induced by the primary failure. This second failure is analogous to that experienced by the Wirraways; see Fig. 6. The section outboard of station 180 then separated and struck the starboard tailplane which failed in turn.

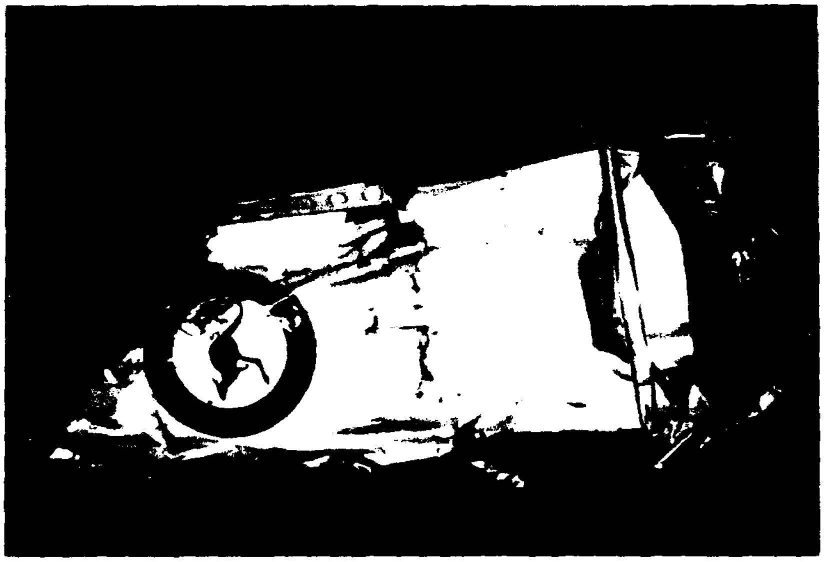


Fig. 10 **A85-416 starboard wing upper surface. Note the deep compression buckle immediately outboard of the wing joint and the missing wing tip. The leading edge damage resulted from impact with the tailplane**

Wing rotation proceeded until the further collapse of the upper surface at station 62 was prevented by the broken ends of the wing joint bolting angles jamming against the upper surface skin. The high bending loads induced by the inertia of the rotating wing were then transferred across the lower surface bolting angles which did not fail. As a result, the wing failed in bending at the wing root (station 24), Fig. 11, and separated from the aircraft.

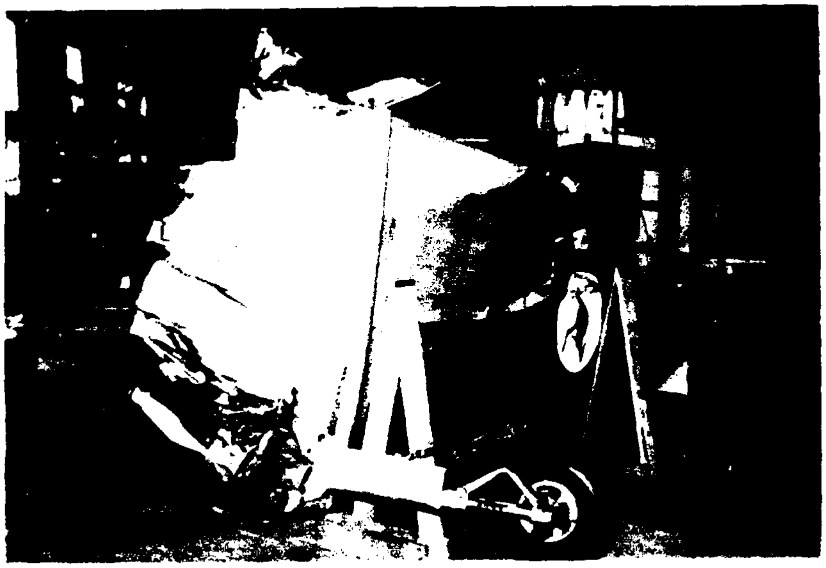


Fig. 11 A85-416 starboard wing lower surface showing the upwards bending failure at the wing root

ARL had previously carried out static strength tests on the Winjeel wing. These showed that, at the accident weight of 4,300 lb, the ultimate failing load of the wing was 10.1g and the mode of failure was identical to the primary failure exhibited by A85-416. Since 7g was the maximum recorded by counting accelerometers in Winjeel aircraft during 678 hours of flying training, it seemed virtually impossible that A85-416 had achieved over 10g in a symmetric manoeuvre on this occasion. Hence, it looked like a rolling pull-out manoeuvre, so the load augmentation provided by a deflected aileron was calculated for various speeds up to 198 KEAS which is 90% of V_{NE} for the Winjeel. These calculations showed that, even if aileron was applied to the limit of the pilot's strength, a load of 7.2g was still required to break the wing. Given the accelerometer recordings, this still seemed unlikely, so that it was necessary to look for some additional factor.

At the time of the accident, the wind was strong and gusty. This was well shown by the Dines Anemograph from the Point Henry lighthouse which is about ten miles west of the accident site. This showed an average wind strength of 35 knots with gusts up to 45 knots. Comparison with wind soundings made at Laverton and Essendon suggests that the mean wind at flight level (5,000 ft) was between 40 and 50 knots. The temperature soundings showed that the atmosphere was somewhat less stable than normal, with a relatively unstable layer between 3,000 ft and 6,000 ft.

The chance of meeting a vertical gust of large magnitude is greatly increased when operating under conditions in which mountain waves are being generated over rough terrain. Winjeel A85-416 was flying on the lee side of a ridge some 450 ft high which forms the spine of the Bellarine Peninsula. While this is not particularly high, the ridge line lay directly across a strong wind which had a clear fetch across some six miles of water. The You Yangs (see Fig. 4) formed a much higher ridge directly upwind at a distance of ten miles, twice the wavelength of the lee waves which could be expected

under the prevailing conditions. In view of the marked strengthening of the wind during the day, these circumstances were suitable for the generation of severe turbulence in the area of the accident.

In Applied Note 4, ARL concluded that the most likely cause of the accident was the simultaneous application of severe gust loads and asymmetric loads resulting from a rolling pull-out manoeuvre. This investigation is of interest because it required a detailed analysis of the low level turbulence to be expected in a specific area under the prevailing meteorological conditions. Such an analysis could not have been performed without specialist expertise; an expertise that was readily available within ARL.

9. SYMMETRIC OVERLOAD

Some examples of structural failure in symmetric overload have already been provided by the wooden wings of the Anson and Mosquito; see Section 7. Modern metal wings rarely fail in this way and, on these rare occasions, it is generally because some unforeseen factor intrudes. On such occasions, identification and quantification of these factors forms a major part of the accident investigation. A good example is provided by the pitch stability of the North American Sabre.

On 1 November 1961, Sabre A94-360 was engaged on an interception mission near Darwin, NT. The aircraft dived from an altitude of 25,000 ft to 3,000 ft while making a mock attack on a Canberra bomber. Near the bottom of the dive, the aircraft suddenly disintegrated and fell into Darwin Harbour. Wreckage recovered from the sea bed was transported to RAAF Laverton where it was re-assembled, Fig. 12.

Fig. 12 Wreckage of A94-360 during re-assembly at RAAF Laverton

An examination of the port wing showed that it had failed in overload bending. Following failure, the port wing had then rolled right over the top of the fuselage, striking the canopy in the process, before impacting the starboard wing. Stencil lettering from the upper surface of the port wing leading edge, Fig. 13, was imprinted on the upper surface of the starboard wing trailing edge, Fig. 14. The starboard wing then separated and moved aft to demolish the starboard tailplane.

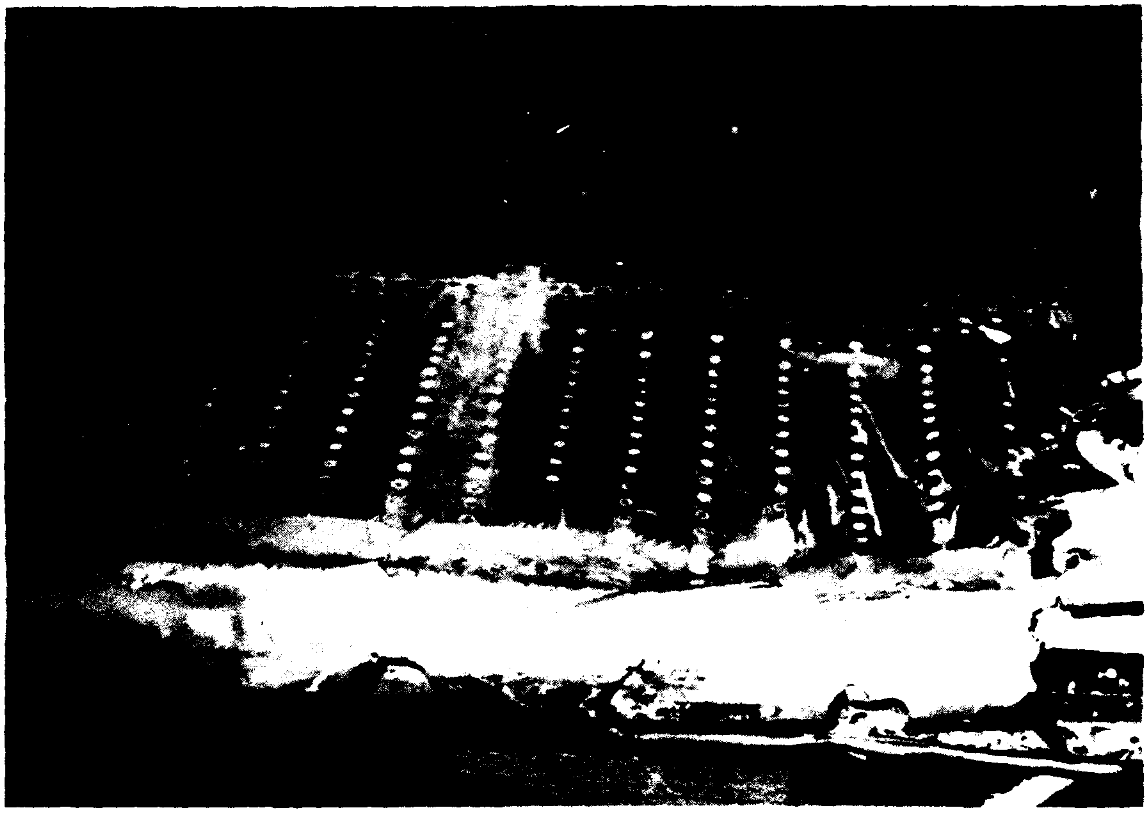


Fig. 13 Lettering on port wing which impacted starboard wing

Fig. 14 Starboard wing upper surface skin imprinted with lettering from port wing

A detailed examination of the port wing showed no evidence of pre-crash defects, fire or explosion. There were no signs of torsional loading such as occurred in a previous accident to Sabre A94-902, and the wing failure was similar to that produced in static strength tests of Sabre wings under the positive high angle of attack (PHA) load case. All of this suggested that the wing had failed in symmetric overload but, since eyewitnesses reported that the aircraft had not commenced to recover from the dive, it seemed unlikely that this could have been induced by the pilot in a straight pull-out. Accordingly, it was necessary to seek some other explanation.

Earlier flight tests had shown that, at high speeds, Sabre aircraft had a tendency to develop pitching oscillations at the short period pitch frequency of about 1.0 Hz. Adequate damping existed at speeds up to Mach 0.88 but, above this speed, the damping decreased to reach zero at Mach 0.96. Any attempt by the pilot to reduce the magnitude of these oscillations by control inputs only resulted in an out of phase correction which increased their magnitude.

An examination of the instrument panel, Fig. 15, showed that the airspeed indicator and the Mach meter were jammed at readings of 600 knots and 0.96 respectively. Collectively, these indicate an altitude of 3,000 ft for an assumed ambient temperature of 22°C. The recording accelerometer showed a maximum value of +9.1g and a minimum of -4.4g, readings indicative of a violent pitching oscillation. Applied Report 29 concluded that the port wing failed in overload bending when pilot action induced a

divergent short period pitching oscillation at the critical Mach number of 0.96 at an altitude of 3,000 ft.

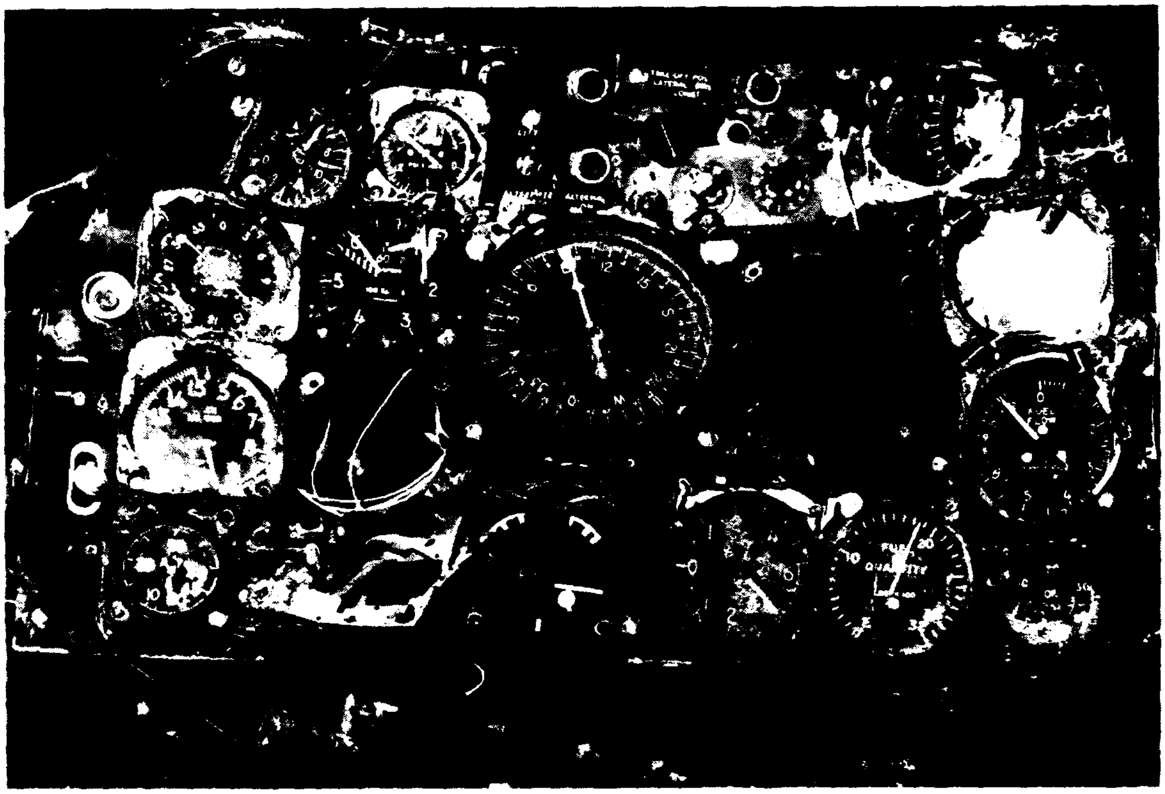


Fig. 15 Instrument panel from A94-360 with Mach meter at left centre

A second, and similar, accident to a Sabre aircraft occurred at Newcastle, NSW on 16 August 1966. While climbing after take-off from RAAF Williamtown on a night flying exercise, A94-358 entered cloud at an altitude of 7,000 ft. About one minute later, eyewitnesses observed the aircraft to be diving steeply when it disintegrated at about 2,000 ft altitude. An examination of the wreckage showed that the starboard wing had failed in overload bending before rolling over the canopy to strike the port wing. Again there was no evidence of any pre-crash defect and all materials complied with specification requirements.

It was considered likely that the pilot lost control upon entering cloud and overstressed the aircraft during the attempted recovery. Unfortunately the instrument panel was too badly damaged to provide any useful data and Applied Report 61 refrained from commenting on the origin of the loads which caused wing failure. These two Sabre accidents illustrate the value of instrument readings. For A94-360, detailed examination of the recovered instruments by expert specialists provided the additional information necessary to determine the cause of the accident with some precision. For A94-358, such information proved unobtainable and the exact cause of the accident remained, to some extent, conjectural.

The third example of structural failure in symmetric overload is of interest because of its complexity. On 26 April 1991, Lockheed P-3C Orion A9-754 took off from Cocos Island and commenced a right hand climbing turn to a height of 5,000 ft above mean sea level (AMSL). The aircraft was then placed into a shallow dive and positioned for a low level pass across the airfield. As the aircraft crossed the runway at 380 knots indicated airspeed (KIAS) and 300 ft AMSL, a straight pull-out was initiated with all engines at full power. At this point, eyewitnesses observed a number of items to separate from the aircraft. A shallow climb was then achieved with the aircraft vibrating violently. The pilot attempted to complete a circuit preparatory to landing but height could not be maintained and the aircraft was ditched into the shallow water of the lagoon.

Water impact occurred with the aircraft in a nose high, slightly left wing low attitude. Because all engines were at full power, torque reaction caused all four propellers to separate from their respective engines when the blade tips touched the water. Since their direction of rotation was clockwise when viewed from the rear, the propellers separated by moving to starboard and the port inboard propeller (No. 2) penetrated the port side of the forward fuselage killing one of the occupants. Similarly, the detached starboard propellers inflicted some damage on the outer section of the starboard wing leading edge, the starboard aileron and the starboard flap. As its speed diminished, the aircraft finally slewed to port and come to rest on the sea bed, Fig. 16.

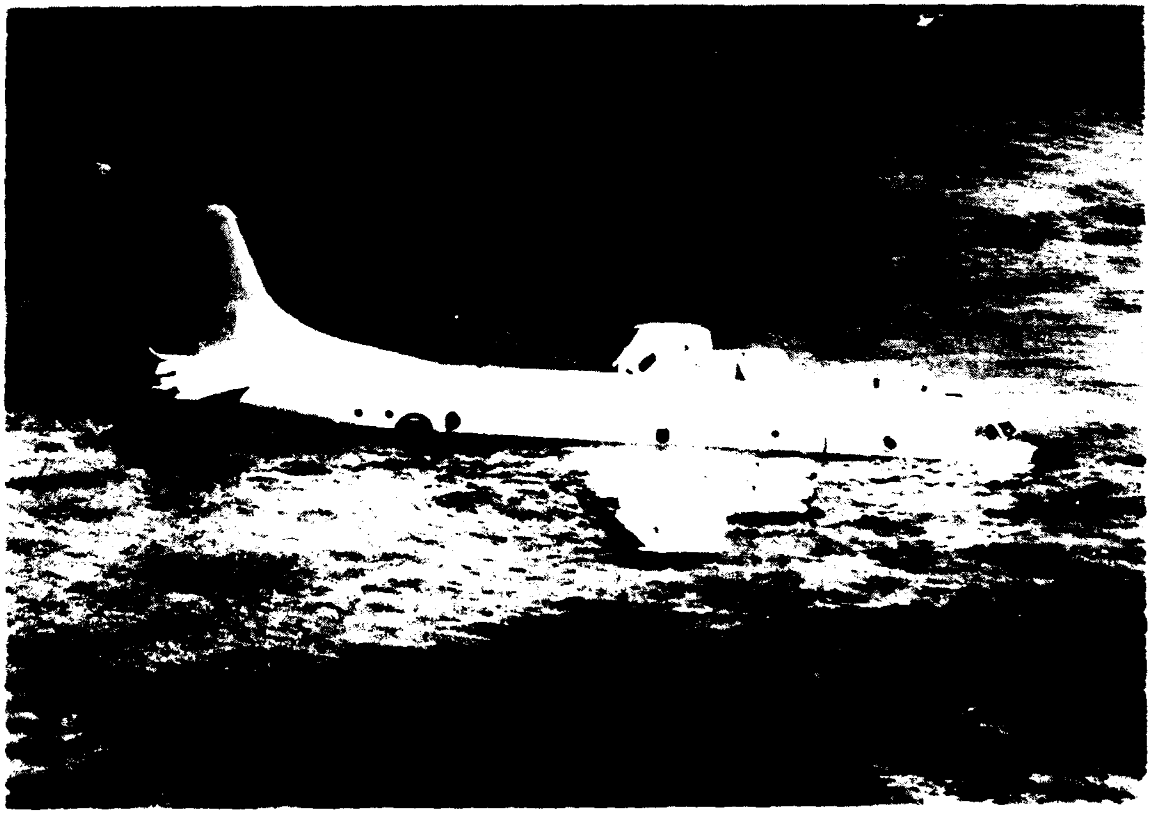


Fig. 16 **Orion A9-754 in the lagoon at Cocos Island. Note the missing propellers**

An in-situ examination of the aircraft revealed that three sections of the wing leading edge, viz. the port centre section between engines 1 and 2, the starboard inboard section and the starboard centre section between engines 3 and 4 had collapsed and broken up in flight. Debris from these sections had passed over the wing to strike both sides of the tailplane and elevators. However, damage to the elevators was far more extensive than could have been produced from debris impact alone; both elevators had failed inboard and outboard of their mass balances, Fig 17, allowing large pieces to separate in flight. The nature of this damage indicated that the elevators had fluttered when excited by the highly turbulent flow consequent upon the collapse of the leading edge sections. Elevator flutter also explained the violent vibration experienced on the aircraft flight deck. Hence it was concluded that elevator damage was secondary and the primary cause of the accident was the collapse of the leading edge sections.

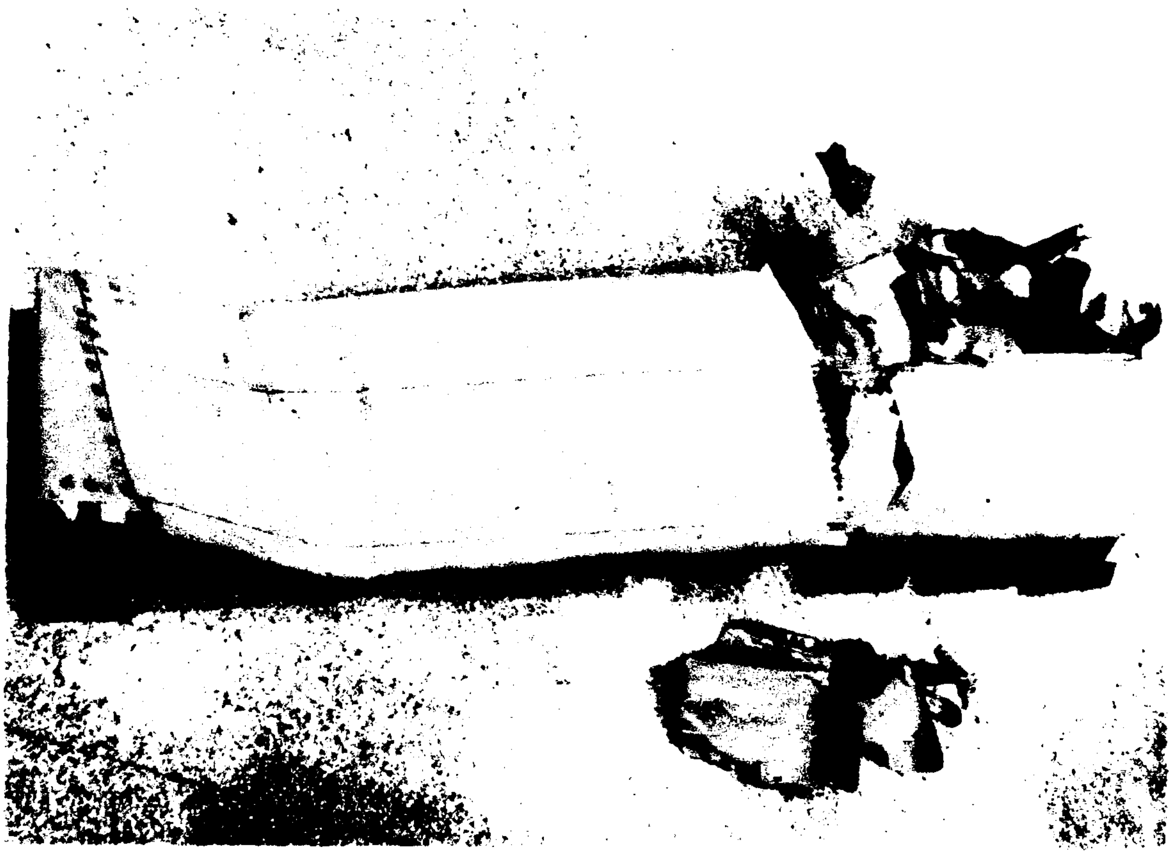


Fig. 17 Outboard section of the starboard elevator showing failure on both sides of the mass balance weights

The distribution of the wreckage showed that the three sections must have collapsed virtually simultaneously. Since the sections were structurally independent, this eliminated any possibility that collapse originated in any isolated pre-crash defect; rather, collapse must have resulted from a set of factors common to all three sections.

Since the Orion wing is of multi-spar design, the leading edge is not part of the primary structure. Each leading edge section consists of a series of D shaped ribs with external skin attached. An examination of the collapsed sections, Fig. 18, showed that collapse resulted from the upwards bending failure of the lower leg of each rib. For each section, collapse had initiated at the outboard rib with the other ribs failing progressively as the failure moved inboard. Once this sequence was established, it became evident that the port inboard leading edge section had also started to fail in this way but failure had not continued to final collapse.

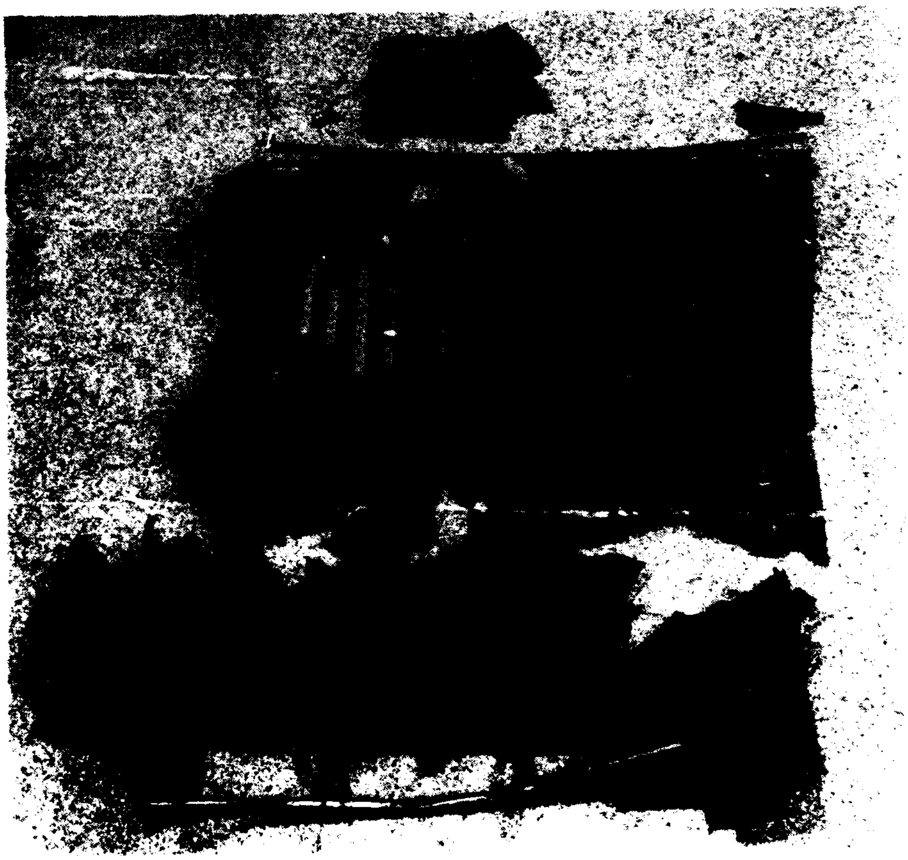


Fig. 18 Starboard inboard leading edge section with the rib lower legs near the top of the photograph

A finite element model was formulated to examine the stress distribution in a typical leading edge rib when bending upwards under the applied aerodynamic loading. This model made use of PAFEC, a standard structural analysis computer code. The model showed that tensile stresses reached a maximum level in the upper flange of the rib lower leg, Fig. 19, and predicted a mode of failure identical to that established from an examination of the wreckage, features which gave confidence in the validity of the model. It therefore looked as if the chordwise pressure distribution had been such as to apply aerodynamic loads to the leading edge in excess of design limits. In this respect,

the situation was analogous to that for the Wirraway accidents mentioned in Section 8. However, under the circumstances of the accident, the nominal aerodynamic loads were far too low to produce the observed failures.

Fig. 19 Finite element model of a leading edge rib showing the stress distribution

In designing the Orion wing, Lockheed used wind tunnel data given in NACA Tech Note 3162 of March 1954. A closer scrutiny of these data provided evidence of greatly increased aerodynamic loads over the leading edge under certain combinations of airspeed and angle of attack (∝). This phenomenon is known as compressibility. On thick section subsonic aerofoils, compressibility is seen as a rapid expansion of the air at or near the leading edge at speeds as low as Mach 0.45. The local Mach number will be supersonic and can reach Mach 2.0 at higher ∝. The area of supersonic flow will be small at lower speeds since the expansion is followed by a compression wave. At higher speeds, the compression wave forms a normal shock wave at a chord position which increases with Mach number.

The wind tunnel data from NACA TN3162 show that, with Mach number increasing from 0.52 to 0.62 and ∝ increasing from 4° to 8°, there is a region where the area of supersonic flow suddenly expands to cover all of the first 15% of chord, i.e. the entire leading edge. The supersonic flow is reflected in the very high suctions recorded over the upper surface as shown in Fig. 20 for a Mach number of 0.57. Since A9-754 was flying at 380 KIAS in an ambient temperature of 28°C, this is the Mach number appropriate to the accident.

For convenience, the pressure distributions for the PHA and PLA (positive low $\propto$) design cases are also shown in Fig. 20. While these curves are not strictly comparable with the raw two-dimensional wind tunnel data, they are sufficiently compatible to suggest that the total lift load on the leading edge for $\propto = 8°$ is roughly double that for the critical PHA design case.

The accident conditions were close to the PLA design case. For these conditions, the aerodynamic loads on the leading edge were computed using TAIR, an aerodynamics computer code which includes transonic compressibility effects. The effects of nacelle interference and propeller slipstream, assuming the engines at full power, were also included. When these revised aerodynamic loads were fed into the finite element model, failure of leading edge sections built to specification was predicted at a load factor of 3.9g. However, detailed measurements of the ribs from the collapsed sections of A9-754 showed these to be approximately 10% below specified thickness. When this factor was included, the model predicted failure at 3.4g.

The primary wing structure of most aircraft could be expected to show some permanent damage above 80-85% DUL. Since the Orion was designed in the non-aerobatic category to have a DLL of 3g and a DUL of 4.5g, this equates to 3.6 - 3.8g. The primary wing structure of A9-754 showed no permanent damage. Hence, the model prediction was fully consistent with this observation and with the fatigue meter readings which showed a single count above 2.65g, the highest threshold level set on the meter.

Design requirements specify that an aircraft structure shall possess a 50% safety margin above DLL over the entire performance envelope. In designing the Orion, Lockheed sought to satisfy this requirement simply by factoring the DLL stresses appropriately. This approach is satisfactory provided there is no significant change in load distribution between DLL and DUL. However, as the accident analysis showed, transonic compressibility effects become apparent a little above DLL at the higher end of the speed range and markedly increase the aerodynamic loads acting on the wing leading edge. This possibility was overlooked in the design of the Orion.

Structures Technical Memorandum 554 concluded that the accident was caused by a combination of three major factors, viz.

a. pilot induced overload in that the pilot exceeded the placard limitation of 3g,

b. manufacturing deficiency in that the leading edge ribs were below the specified thickness,

c. design deficiency in that transonic compressibility effects had been ignored.

A reduction in placard limits was recommended. Lockheed carried out an independent investigation of this accident using a fairly crude finite element model and with aerodynamic loads derived from QUADPAN, an aerodynamics computer code specifically restricted to subsonic flow. They concluded, predictably, that the Orion fully met the design requirements and the accident could not possibly have happened in the way in which it did.

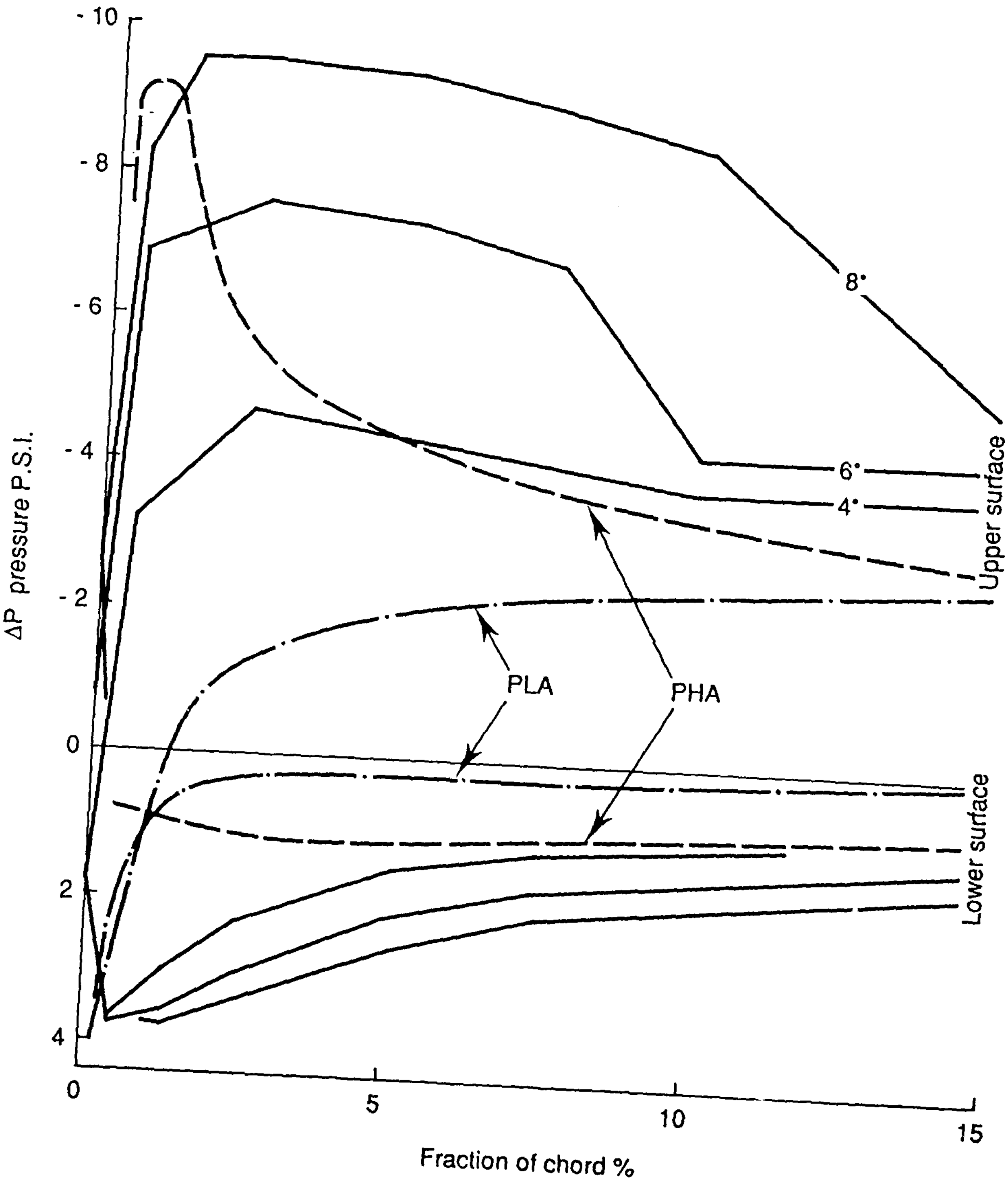


Fig. 20 **Chordwise pressure distributions at M0.57 for various angles of attack. NACA 64A410 section**

The accident to A9-754 had an interesting postscript. While investigating the accident, ARL was made aware of a similar accident to a US Navy Orion, also at Cocos Island, some three years earlier. The USN Orion was making a high speed, low level pass along the airfield when it commenced a rolling pull-out manoeuvre and the starboard leading edge centre section collapsed. Despite violent vibration and severe control difficulties, the aircraft was landed successfully.

Upon landing, the fatigue meter showed one count above 3g but no counts above 3.5g. At 320 KIAS (Mach 0.47), the aircraft speed was probably a little below the compressibility threshold for a symmetric manoeuvre. However, the aircraft was rolling to starboard and this roll would increase the effective angle of attack and the flow velocity for the starboard wing. Thus this accident was more directly analogous to the Wirraway accidents than that of A9-754. The accident was investigated by the US Navy, with technical support provided by Lockheed. They concluded that the leading edge section collapsed for undetermined reasons with pilot induced overstress as a contributing factor. With the ARL analysis, the reasons were no longer undetermined.

10. ENGINE FAILURE

ARL has investigated many engine failures with a view to establishing the exact cause of failure so that appropriate corrective action may be taken. This frequently requires a complete strip down of the engine so that suspect components may be identified and examined for overheating, excessive wear, defective materials, faulty assembly, etc. In most cases, an engine failure does not result in a serious accident and the investigation becomes a straightforward exercise which combines the skills of the engine experts and the metallurgists. Occasionally, a serious accident does result and, in the subsequent investigation, alternative explanations are progressively eliminated until attention is focussed on the engine.

For propeller driven aircraft, a quick inspection of the propeller blades will provide a qualitative impression of the amount of power being developed by the engine at ground impact. However, there are traps for the unwary. The standard accident investigation manuals always state that if the blades are bent rearwards, then the engine was developing little or no power; if bent forwards, then the engine was developing high power. The manuals fail to mention that this only applies if the aircraft is in a substantially flat attitude at ground impact. For an aircraft impacting the ground at an appreciable dive angle, the propeller blades will still be bent rearwards even if the engine is at full power. It all depends on the angle between the blade tip, allowing for the thrust or drag induced bend in the blade, and the plane of the ground.

A better impression is gained from the degree of damage to the blades. If that damage consists of little more than a single smooth bend, then the engine was developing very little power. If on the other hand, the blades have been deformed into convoluted shapes, then there was plenty of power on and the Wirraway propeller shown in Fig. 4 is a good example. Of course, the nature of the impacting surface is a complicating factor. When Orion A9-754 contacted the water of Cocos Island lagoon, Fig. 16, the propeller blades were relatively little damaged despite the high power being developed by the engines. However, when Pilatus Porter A14-702 crashed at Point Cook, Vic. on 7 December 1983, the propeller blades showed multiple fractures and were little more than a tangled mess.

In this accident, the aircraft was in the process of recovering from a stall with full power applied when it hit a concrete apron.

A more complex example is provided by Pilatus PC-9 A23-035 which crashed at East Sale, Vic. on 5 August 1991. In this accident, the propeller contacted a wire fence before striking the ground. The variation in blade damage is shown in Fig. 21 where the blades are numbered 1 - 4 in sequence from right to left. As may be seen, blade 4 picked up fence wires and was pulled into a smooth rearwards bend as the wires stretched. Blade 1 cut through the fence post shown at far right losing its tip in the process. Blades 2 and 3 missed the fence and were slightly twisted, but not bent, on ground impact. At first sight, the small damage to blades 2, 3 and 4 would seem to suggest that the engine had failed and was not delivering any power. However, for blade 1 to cut completely through a thick post of dry hardwood means that some power must have been developed and Structures Technical Memorandum 582 estimated this as 15% of full power.

Fig. 21 Propeller blades from A23-035 with the fence post cut through by blade 1 at right

Shortly after taking off from Mallala, SA on 10 November 1957, Mustang A68-123 stalled and crashed, Fig. 22. The pilot was killed in the accident. At first sight it looked like a typical pilot error accident but eyewitnesses heard the engine backfire and observed a copious emission of black smoke just before the aircraft stalled. An inspection of the

propeller blades showed these to have the classical smooth rearwards bend normally associated with low power output. A strip-down examination of the Rolls-Royce Merlin revealed that the flame traps were severely damaged. These flame traps were build up from sheets of copper alloy to form a fine mesh honeycomb within the intake manifold. A considerable amount of this material was found in the cylinders with pieces lodged under inlet and exhaust valves thus preventing them from closing. Further examination revealed a broken inlet valve seat and this probably induced the backfire which initiated failure of the flame traps.

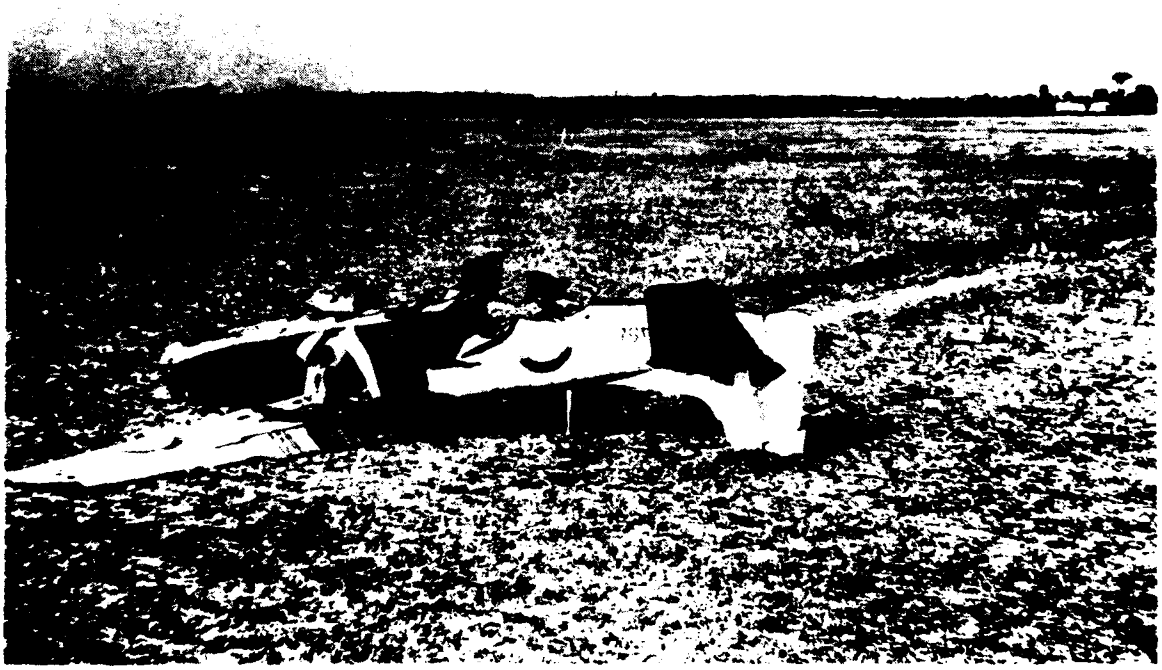


Fig. 22 The wreckage of A68-123 with its detached propeller in the distance

Applied Technical Memorandum 6 concluded that the aircraft crashed subsequent to a complete loss of power at an altitude of 500 ft. This conclusion was supported by the evidence of a previous incident in which a Merlin engine in an Avro Lincoln failed when particles of flame trap lodged under valves. On that occasion, failure was attributed to a fractured valve seat and a modification was introduced requiring a different type of valve seat to be incorporated in Merlin engines. This modification had not been carried out on the engine of A68-123.

Inadequate maintenance was responsible for the failure of an engine in Gloster Meteor NF.11, serial WM374 at Woomera, SA on 21 May 1958. The aircraft was performing a touch and go landing when, on applying power to go around, the starboard engine failed when the aircraft was about 30 ft above the runway. Eyewitnesses reported a loud

rumbling noise with the aircraft yawing noticeably to starboard before it climbed away with the starboard engine visibly on fire. The pilot elected to complete the circuit but, when about half way around at an altitude of 800 ft, the rear fuselage failed, the tail unit separated and the aircraft crashed killing the pilot.

An examination of the Rolls-Royce Derwent engine showed that the turbine disc had fractured allowing a substantial portion to separate, Fig. 23. The fracture originated at the rim in a region where high temperature intercrystalline corrosion had promoted the development of intergranular cracking. The Derwent maintenance schedule required re-machining of the disc after every 200 hours of running time to remove corrosion affected material. This had not been done in the 323 hours that the engine had been in WM374. According to Applied Technical Memorandum 10, this omission was the primary cause for the engine failure. Fuel, leaking from punctured fuselage tanks, ignited and burnt in the rear fuselage until the heat-softened structure failed. Elapsed time between turbine disc failure and rear fuselage failure was estimated as 55 seconds; an ominous example of the intolerance of aluminium alloys to fuel fires.

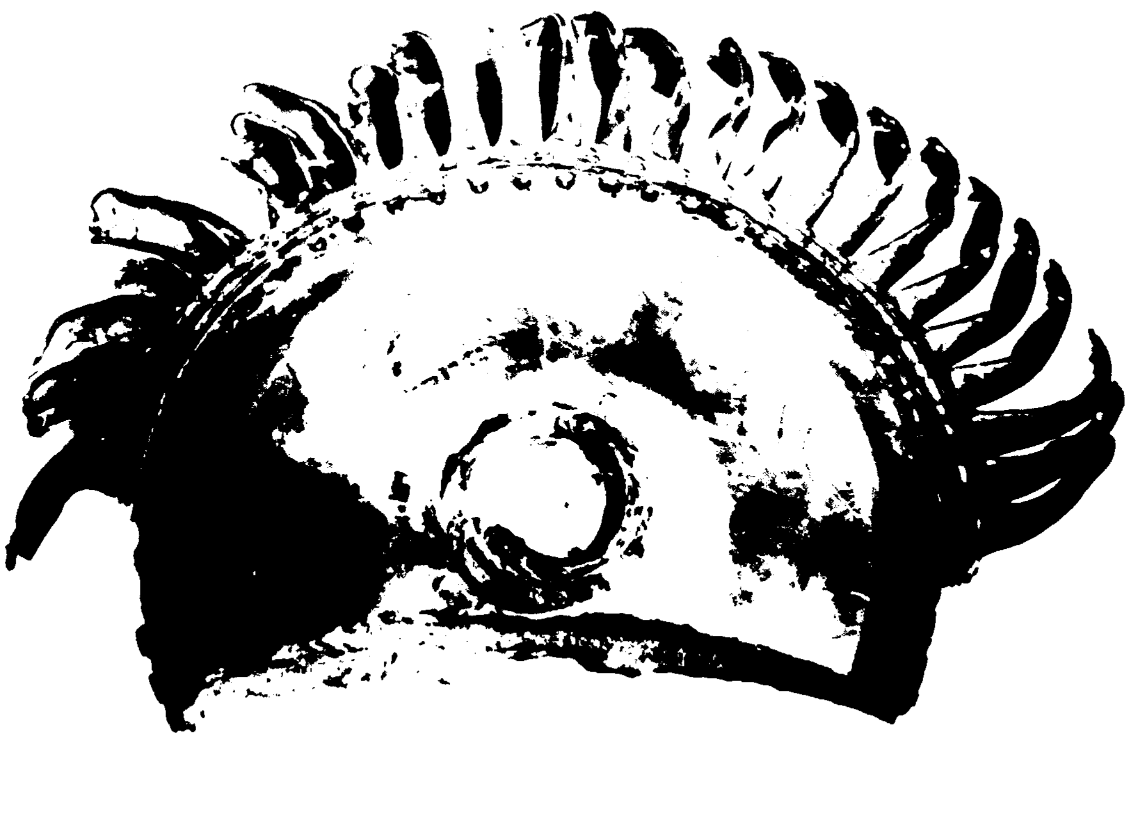


Fig. 23 Fractured turbine disc recovered from the wreckage of WM374

Further examples were provided by the Macchi MB.326H. During night flying exercises on 22 July 1969 at East Sale, Vic, Macchi A7-007 crashed shortly after take-off. One pilot ejected safely but the other remained in the aircraft and sustained fatal injuries. The surviving pilot reported that the take-off had proceeded normally with the engine at full

145 KIAS, the overheat warning lights and the master caution light illuminated but the fire warning lights did not. He elected to complete a low level circuit and commenced a 20° banked turn away from the runway when there was a muffled bang and all elevator control was lost. Eyewitnesses testified that the take-off appeared normal but that an in-flight fire was visible shortly after lift off. Ground impact occurred approximately 27 seconds later.

In the Macchi, the Rolls-Royce Viper engine is mounted in the rear fuselage. The annular space between the engine and the rear fuselage structure is sealed by a stainless steel firewall placed at the junction of the engine hot and cold sections. All fuel system components are located forward of the firewall and, aft of the firewall, the annulus is cooled by air from four external scoops, two above and two below the rear fuselage. Fire warning and overheat warning sensors are fore and aft of the firewall respectively.

An examination of the wreckage provided ample evidence that an intense fuel fire had burnt in the rear fuselage annulus aft of the firewall. External paint was blistered, Fig. 24, the interior was coated with soot, and some areas had been sprayed with molten aluminium. Bellcranks and push rods, of 2014 aluminium alloy, of the elevator and rudder control circuits had melted and this, obviously, was responsible for the loss of control. It seemed clear that fuel had somehow entered the region to be ignited by the hot engine tailpipe. However, the firewall was recovered intact and it seemed unlikely that fuel could have leaked past its seals.

Fig. 24 The tail unit of A7-007 came to rest against the verandah of a house just outside the boundary of East Sale Aerodrome. Note the blistered paint on the tail cone

From the pattern of the internal soot coating, fuel had apparently entered through the two lower scoops. ARL combustion experts calculated that, at 140 KIAS, these scoops would need to ingest fuel at a rate of 3.3 lb/min in order to achieve a stoichiometric mixture. Further examination of the engine disclosed a failed gasket at the junction of the barometric fuel control unit (BFCU) and the augmentor valve. Failure of this gasket would produce a fuel leakage rate well in excess of that required. Once established, these facts enabled Applied Report 68 to postulate the following accident sequence.

a. The gasket sealing the BFCU - augmentor valve junction failed allowing high pressure fuel at 680 psi to spray into the engine bay forward of the firewall.

b. The leaking fuel drained into the airstream through vents in the floor of the engine bay.

c. Leaking fuel was ingested by the lower cooling air scoops aft of the firewall.

d. The fuel/air mixture within the rear fuselage was ignited by the hot tailpipe to produce an intense fire. The overheat warning light illuminated.

e. Rudder and elevator control circuits within the rear fuselage melted and failed, Fig. 25.

ARL recommended that the gasket material be changed in order to prevent any recurrence.

Fig. 25 Central bellcrank assembly from A7-007 showing areas of local melting and failed control rod

Macchi A7-085 crashed near Williamtown, NSW on 19 August 1985 during a gunnery training exercise. Eyewitnesses reported the aircraft trailing white smoke followed, after a period, by the appearance of visible flame. The pilot noted fire warning and overheat warning lights on, followed by loss of rudder control before he ejected successfully.

To the ARL investigators, the appearance of the wreckage was decidedly familiar. The gasket at the BFCU - augmentor valve junction had failed and an intense fire had burnt in the rear fuselage aft of the firewall causing control system push rods to fail. A second fire of low intensity had burnt in the engine bay forward of the firewall and this was responsible for the fire warning reported by the pilot. Microscopic examination of the four lamp filaments, two fire warning and two overheat warning, confirmed that all were on at ground impact. Further microscopic examination showed the augmentor valve gasket to be sub-standard, indicating that earlier lessons had been forgotten.

Not all engine examinations confirm that the engine had failed. Frequently an examination confirms that the engine was operating normally until ground impact enabling engine failure to be eliminated as a factor contributing to the accident. When Canberra A84-205 suffered a loss of control and crashed at Amberley, Queensland on 23 March 1970, failure of one or both engines was suspected. However, a detailed strip examination of both Rolls-Royce Avons showed that they were delivering high power at ground impact and there was no evidence of any in-flight failure. Accordingly, ME Tech Memo 334 concluded that the engines were operating normally and that engine malfunction was not a factor in the accident.

Damage to compressor blades, or fan blades in large turbofan engines, is analogous to propeller blade damage. On 29 October 1991, Boeing 707 A20-103 stalled and crashed into Bass Strait. There were no survivors. At the time of the accident, the aircraft captain (a qualified B707 flying instructor) was demonstrating flight at Vmca (Velocity Minimum Control Air), an exercise which involves the application of asymmetric power. Determination of the power being developed by each of the four engines was seen as a critical aspect of the accident investigation.

The damage sustained by the four engines at sea impact is compared in the following figures with the engines numbered sequentially from port to starboard. In Fig. 26, the fan blades of engine No. 1 have suffered only minimal rotational damage, many are still attached to the hub, indicating that the engine was almost stationary at sea impact. The situation was complicated by the fact that engine No. 1 separated from the aircraft as it stalled and was recovered from the sea bed some distance from the main wreckage. Obviously, it would have commenced to run down on separation but, as calculations showed, its time of fall to sea impact could not have exceeded 17 seconds. This is a very short run-down time for a large turbofan engine and suggested that the engine must have been operating only at very low power when it separated.

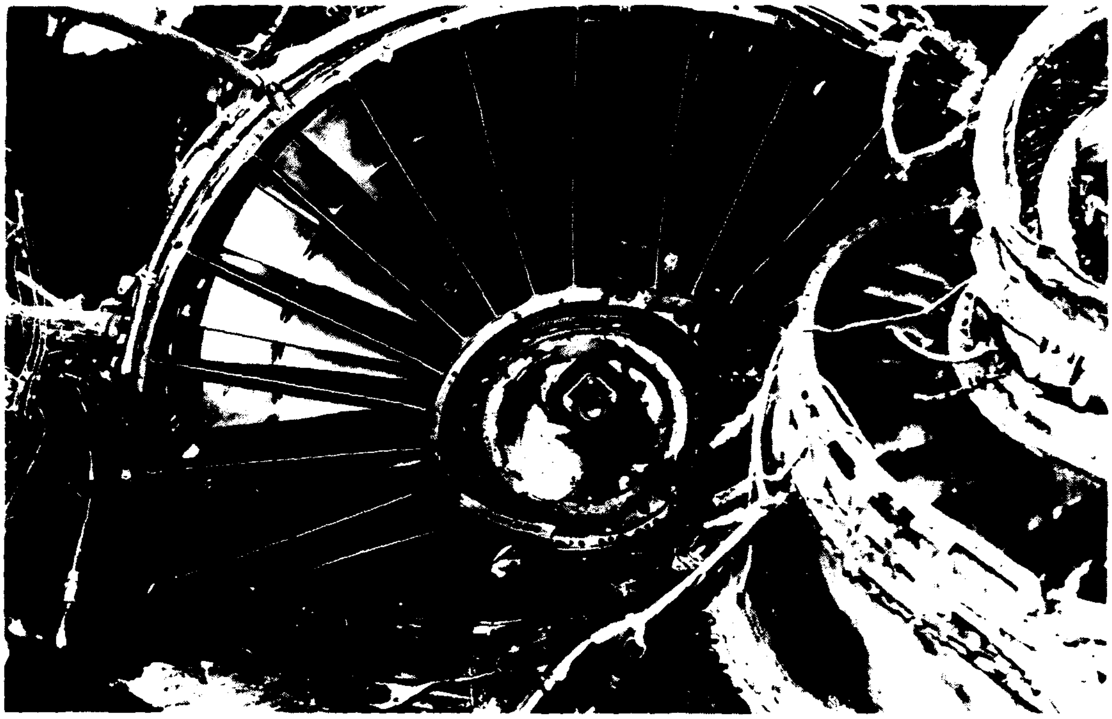


Fig. 26 **Fan stage of engine No.1 from A20-103 showing minimal rotational damage to blades**

The other three engines remained attached to the aircraft until sea impact. On recovery from the sea bed, the fan blades of engine No. 2 showed a somewhat greater degree of damage, Fig. 27, indicating that the engine was rotating slowly but significantly faster than No. 1.

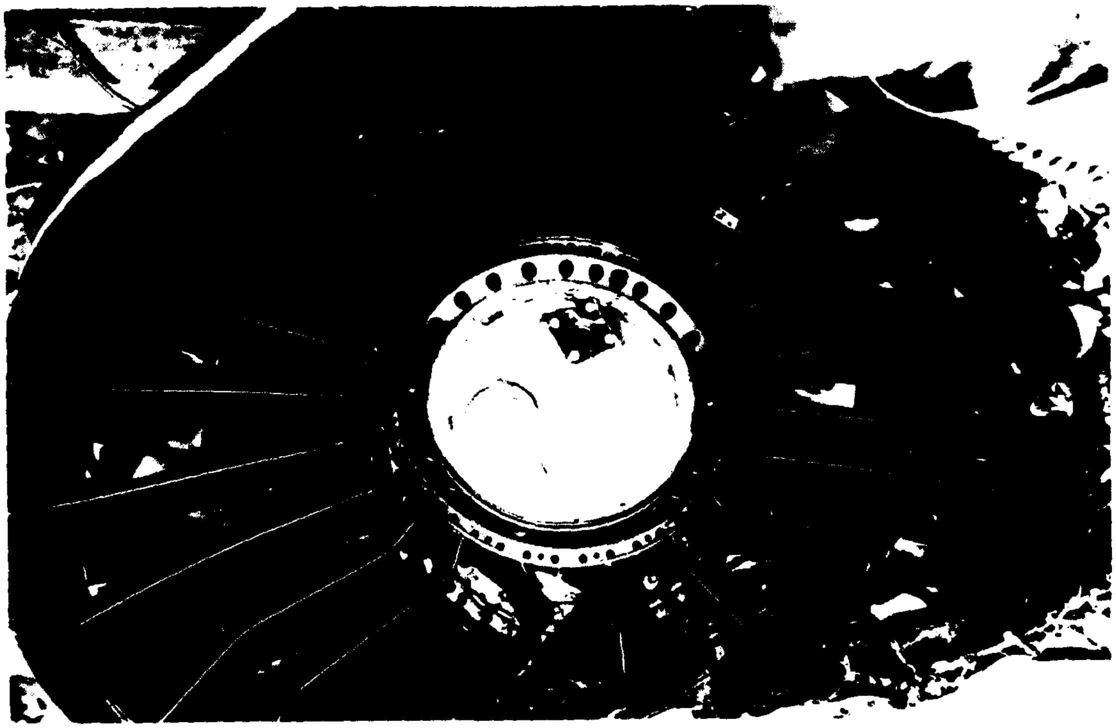


Fig. 27 **Fan stage of engine No. 2 as recovered. The blade damage is still small although greater than that for engine No. 1**

Figure 28 shows the extensive fan damage of engine No. 3 with all blades stripped from the hub. The severity of the damage indicates that the engine was rotating at high speed when impact occurred. The fan drive shaft of engine No. 4 sheared from the compressor, Fig. 29, again indicating high speed rotation. Damage to the compressor blading was typical of the damage exhibited by the two starboard engines.

Fig. 28 Engine No. 3 with all fan blades stripped from the hub

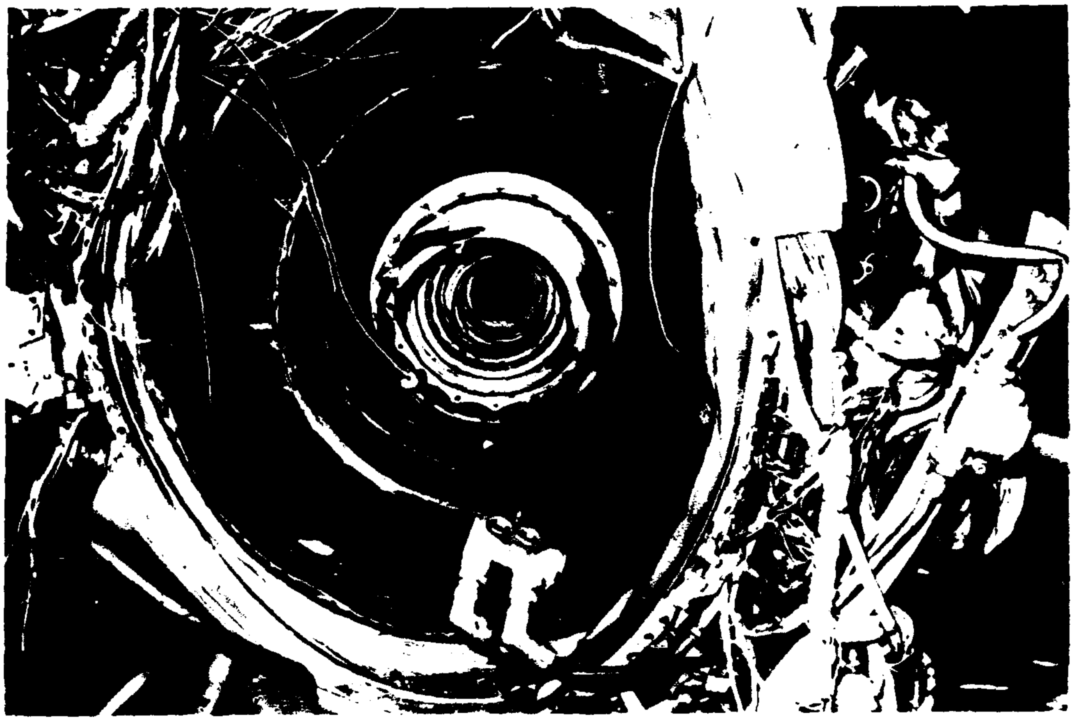


Fig. 29 **Front view of engine No. 4 as recovered showing the compressor damage and the sheared fan drive shaft**

The various instruments, switches, warning lights and controls of the pilots' panels, the central control console and the flight engineer's panel were also examined in detail to determine their readings and settings. The settings of the engine power levers were assessed as:

- Engine No. 1 0 (flight idle)
- Engine No. 2 10% full power
- Engine No. 3 80% full power
- Engine No 4 60% full power

These settings were fully consistent with the observed engine damage. Their validity was generally supported by instrument readings of engine speed, fuel flow and engine oil temperature and pressure. Perhaps the best supporting evidence came from the exhaust temperature gauges which showed readings of 20° C, 160° C and 700° C for engines 1-3 respectively. No reading could be determined for engine No. 4.

To complete this exhaustive examination, the fuel control units of engines 1 and 2 were dismantled for inspection. No significant impact markings were evident on the speed setting cams which would indicate their position at impact. The units for engines 3 and 4 were not dismantled as it was considered that no further useful information could be gained from their internal examination. Despite all the latest scientific aids, the highly polished skills and experience of the experts cannot analyse evidence that isn't there.

11. FLUTTER

Flutter is a self-excited oscillation which occurs when sufficient energy is absorbed by the aircraft structure from the airstream to overcome the damping present and promote structural instability. Above some critical airspeed (flutter speed) the oscillation is divergent and proceeds with ever-increasing amplitude until the structure fails. Since flutter arises from the interaction of oscillatory aerodynamics with the structure, any changes to those aerodynamics, particularly by modifying control surfaces, will alter the flutter speed. Similarly, changes to the mass or structural stiffness distributions of the structure will alter the flutter speed. Clearly, flutter can be a can of worms for the aircraft designer and aircraft accident investigator alike.

Flutter has already been mentioned in connection with the Puss Moth accidents, see Section 4. As originally designed, the ailerons of the Puss Moth were not mass balanced. Then mass balances were fitted but the balance arms were too short to bring the aileron CG forward of the hinge line. When longer balance arms were fitted, the problem was solved. Aviation Publication 970, Design Requirements for Aeroplanes, states that for control surfaces having little or no forward aerodynamic balance, the CG shall always be on, or forward of, the hinge line.

A good example of the effect of an ill-considered change to a control surface is provided by the North American Mustang. Early models of the Mustang had fabric covered elevators. Late in its production life, metal covering was substituted without any increase in the mass balances. This moved the elevator CG aft of the hinge line to the extent that a 14% increase in mass balance was required to move it forward to the original position. Thus the oversight contravened the requirement of AP.970 and led, predictably, to a series of accidents.

On 2 June 1950, Mustang A68-13 was performing a dive bombing exercise at Pearce, WA. This required diving at 60° to about 360 knots before bomb release. Immediately after bomb release the port wing failed and separated from the aircraft together with the horizontal tail surfaces. An examination of the wreckage showed that the port wing had failed in overload bending before separating to strike the canopy and port tailplane in that order, Applied Report 1. The wing was free of pre-crash defects and had failed at a load well in excess of the DUL. Both port and starboard elevators had broken up more extensively than would be expected from purely static overload with the various pieces progressively separating from the tailplane before the tailplane failed.

Significantly, most of the starboard elevator including its mass balance, was not recovered. It was presumed that these had been the first items to separate and lay beyond the search area, further back along the wreckage trail. From all of this evidence, ARL concluded that flutter resulting from inadequately mass balanced elevators, was the primary cause of the accident. This accident highlighted two of the most important clues to flutter induced accidents, the multiple structural failures and the separation of mass balances, features which were evident in the Puss Moth accidents.

While this investigation was in progress, ARL's attention was drawn to three similar Mustang accidents which had occurred previously:

- A68-501 Townsville, Queensland, August 1945
- A68-97 Werribee, Victoria, 6 December 1947
- A68-802 Iwakuni, Japan, 3 December 1948

For A68-501, the evidence available was incomplete. The others suffered failure of the port wing with multiple elevator damage while diving at high speed. While the failure to refer A68-501 and A68-802 to ARL is perhaps understandable on account of their remoteness, the same failure with respect to A68-97 is inexcusable. In none of these four Mustang accidents did the pilot survive.

ARL's involvement with flutter received its major impetus from the Jindivik radio-controlled target aircraft. In its early years, Jindivik was plagued by flutter problems, the result of squeezing the maximum possible performance out of a minimum cost airframe. There were problems with flap flutter, solved by fitting simple static stops to the flaps to prevent them adopting negative angles. There were problems with high frequency aileron "buzz" flutter, solved by fitting a full-span aileron mass balance. Thus configured, the mass balance became part of the aileron structure and markedly increased its torsional stiffness.

Early theoretical analyses of the body freedom flutter characteristics of the aircraft indicated that the calculated critical flutter speed was dangerously low. Trials KA41, KA49 and KA50 were therefore flown at Woomera, SA with an instrumented aircraft to examine the problem. The first two trials were completed successfully but, during KA50 on 10 February 1952, Jindivik A92-29 broke up in flight. An examination of the wreckage showed that the starboard wing had failed in upwards bending and disintegrated, both wing tip AMPOR pods had failed in downwards bending, the port tailplane had disintegrated in downwards bending but the starboard tailplane was substantially intact. The starboard elevator was still attached to the tailplane but jammed in a hard up position. Both elevator mass balances had separated and fracture surfaces showed evidence of oscillatory loads.

Significantly, the fuselage had failed in downwards bending at stations 130 and 162 allowing the forward and rear sections to separate from the centre fuselage which broke up completely, Fig. 30. The underwing fairing, which clips into place to form the bottom of the centre fuselage, separated and was not recovered. All of this evidence is indicative of flutter and Applied Report 2 suggested that flutter in some body freedom mode which involved the elevator was likely.

Fig. 30 **Wreckage of A92-29 re-assembled to show the multiplicity of structural failures**

When Jindivik A92-45 broke up in flight during Trial KA53 on 23 February 1956, Applied Report 3 noted that the wreckage showed all of the main features previously observed on A92-29 except that, this time, it was the port wing which failed in upwards bending and disintegrated, Fig 31. Both sides of the tailplane had failed in upwards bending before the entire tail unit separated. This time, ARL happily embraced a Government Aircraft Factory (GAF) hypothesis that the failures initiated with the collapse of one flap.

Fig. 31 **Upwards bending failure of the port wing of A92-45. Note the fuselage failures at stations 130 and 162 and the break-up of the centre fuselage. The underwing fairing was not recovered**

The litany of disaster continued on 11 April 1956 when Jindivik A92-51 broke up in flight during Trial KA66. Again the familiar pattern of multiple failures of wings, fuselage and tailplane was evident. In the ARL report on this accident, it is possible to discern a growing uncertainty. Applied Report 4 avoids positive statements and concludes that the accident may have resulted from either autopilot malfunction, or aileron flutter, or separation of the canopy, or buckling of the wing leading edge, or, most likely, something else. This time the underwing fairing was recovered and from a position which suggested that it had separated 0.3 seconds before general break-up. This interval was too short for its significance to be appreciated.

Since A92-29 contained some flight test instrumentation, the nature of the flutter encountered by this aircraft was analysed in some detail and reported in S & M Note 229. According to this report, the flutter encountered closely resembled the theoretically predicted behaviour with respect to speed, frequency and mode of oscillation. The mode was described as combining fundamental wing bending with the rigid body motions of pitch and heave. This comfortable conclusion increased confidence in the validity of the theoretical analysis but ignored the existence of the fuselage failures; failures which could hardly be explained within the terms of the described mode.

Jindivik A92-90 broke up in flight at Woomera on 25 September 1958 as it accelerated following a loss of control, Fig. 32. In this accident, the familiar pattern showed some variation; after the wings had failed in upwards bending, their leading edges had been severely damaged when they slammed together. Damage to the tail unit was noticeably less severe and, although the elevators had failed in torsion, they had not detached from the tailplane nor had their mass balances separated, Fig. 33. Again the underwing fairing was nowhere to be found within the wreckage area and was not recovered despite an extensive search. However, this time the ARL report was more confident and Applied Technical Memorandum 11 concluded that the aircraft broke up at the critical flutter speed for the wing although the reason for the loss of control could not be established.

Fig. 32 **A familiar pattern of fuselage failure. The forward fuselage of A92-90 after failure at station 130**

Fig. 33 Tail unit of A92-90 showing damaged elevators with mass balances still attached

Jindiviks A92-413 and WRE.493 broke up in flight on 19 February 1965 and 14 March 1968 respectively. Neither of these accidents was investigated by ARL. From an examination of the wreckage layout of A92-413, Fig. 34, the investigating authority concluded that break-up had been initiated by failure of the fin since fin pieces were furthest from the aircraft flight path. Changes to fin manufacturing procedures were recommended. This accident was significant in that it provided the first positive indication that separation of the underwing fairing preceded break-up.

Experience has shown that, following break-up, light wreckage items lose their forward velocity almost immediately and then drift downwind, Structures Note 427. While these items are scattered by turbulence, in most cases they remain within a sector defined by angles of ± 15° about the direction of the mean wind and with apex below the point of break-up. If these concepts are applied to Fig. 34, it is clear that the underwing fairing separated some 3.5 - 4.0 sec. before general break-up since it is well back along the flight path from the 30° light wreckage sector. For the fairing to separate in this way, a gross distortion of the fuselage in upwards bending is required.

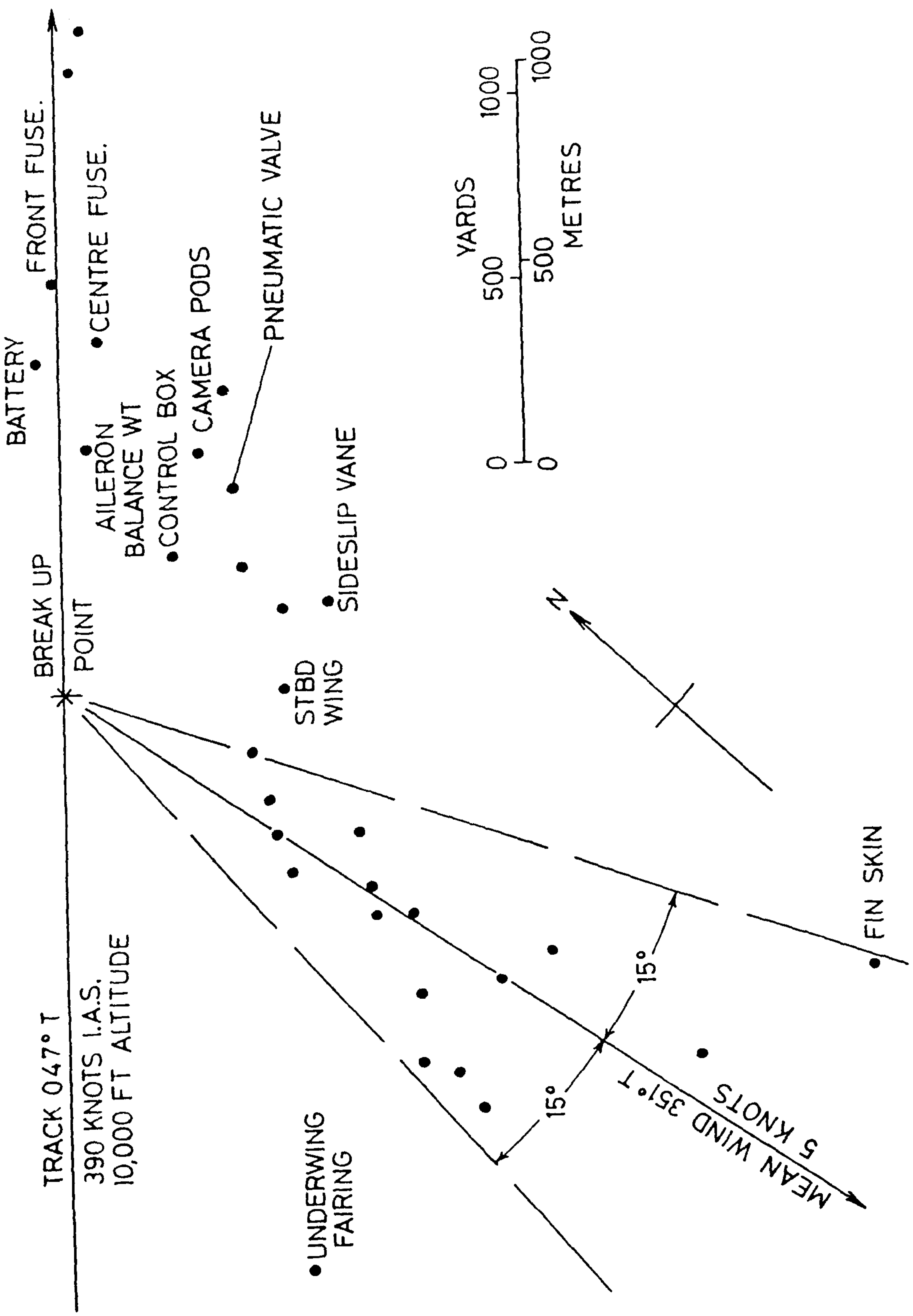


Fig. 34 **Jindivik A92-413 Woomera 19 February 1965**

On 15 July 1969, Jindivik WRE.521 disintegrated in level flight at 490 KIAS while decelerating from a high speed run to 535 KIAS. The wreckage showed all of the familiar features, viz. upwards bending failure of the port wing, downwards bending failure of the fuselage at stations 130 and 162, and failure of the tailplane. Since WRE.521 was a fully instrumented aircraft, it was possible to analyse the behaviour of the aircraft immediately prior to break-up. Telemetry records indicate that, at 9.13 sec. from instrumentation timing datum, the aircraft encountered an 0.8g gust which excited three distinct modes of oscillation, viz:

a. a 40 Hz vibration of the tailplane incidence vane which was damped out by 9.25 sec.

b. a complex mode at around 11 Hz combining wing symmetric torsion and rigid body pitch with a certain amount of autopilot gyro crate response: substantially damped out by 9.35 sec.

c. an unstable mode induced by the elevator at 2 Hz combining the autopilot pitch response characteristics with fuselage pitch and bending out of phase with symmetric wing bending. This mode diverged in amplitude until the aircraft broke up at 9.75 sec; a graphic example of the speed with which catastrophic flutter develops.

The inclusion of fuselage bending was important since it meant that the pitch motion sensed by the autopilot pitch rate gyro, mounted in the nose of the aircraft, was not that appropriate to rigid body pitch. No flutter calculations had been performed for Jindivik which provided for fuselage bending. Applied Technical Memorandum 24 concluded that excitation of the low frequency mode was responsible for the accident to WRE.521 and, probably, for many other Jindivik accidents including all those mentioned in this section. Subsequent body freedom flutter calculations, carried out by GAF, confirmed the validity of this conclusion.

The question remains, why did it take so long to sort out the body freedom flutter problems of the Jindivik? With the benefit of hindsight, it is clear that the behaviour of A92-29 was interpreted in conformity with the results of the theoretical analysis. The investigators were unduly influenced by a fortuitous agreement in flutter speed and, to some extent, in modal behaviour. A significant difference in frequency, 3.1 Hz as against the calculated frequency of 4.2 Hz, was seen as insignificant. However, at the lower frequency, the autopilot pitch response characteristics allowed coupling between the elevator and the body freedom mode whereas, at the higher frequency, they did not. These Jindivik accidents illustrate the dangers of the preconceived idea and emphasise the need to approach all accident investigations with an open mind.

There was also a tendency to ignore some features of the wreckage. While the wing, AMPOR pod and tailplane failures could be explained in terms of the theoretical rigid body mode, the fuselage failures at stations 130 and 162 could not. At the time, this problem was glossed over by regarding the fuselage failures as secondary and consequent upon break-up of the wings, although how an upwards bending failure of one wing could initiate two separate downwards bending failures of the fuselage was never explained. Damage does not occur without a cause; that cause must be identified and explained. In

When Nomad N24-10 crashed at Avalon, Vic. on 6 August 1976, there was not much doubt about the cause of the accident; one eyewitness described the tailplane behaviour as 'like a rag flapping in a strong wind'. Following take-off, the aircraft climbed normally until, at 950 ft altitude and approximately 110 KIAS, control was lost. The aircraft then completed a 180° turn to a downwind heading while descending steeply and struck the ground 1 min. 34 sec. after commencing the take-off roll. Two of the three occupants were killed in the accident. The testimony of the flight test engineer, who survived the accident, plus the evidence of the wreckage, confirmed that the tailplane had fluttered in flight. Flutter had resulted in structural damage to the tailplane with a consequent loss of control. The question put by the Department of Transport to ARL was why had the flutter occurred at such a low airspeed?

At the time of the accident, N24-10 was being used in the N24A development program. One aspect of this program required improved stick force characteristics for the 20° flap configuration. As originally designed, the N22 Nomad used an all-moving tailplane fitted with geared anti-balance tabs extending over the inboard 68% of the span. In order to achieve the desired improvement, various modifications were made to the tailplane including successive increases in tab span, initially to 85%, then to 100% of the tailplane span. In addition, trailing edge T strips, either one inch or two inches wide, were fitted to limited sections of the tailplane and tabs. None of these modifications produced other than a marginal change in the stick force gradient during flight tests. Finally, two inch wide T strips were fitted over the entire length of full span tabs and the aircraft was making its first flight in this configuration when the accident occurred.

A theoretical analysis of the tailplane flutter immediately encountered difficulties with the structural and aerodynamic representations of the tailplane in the accident configuration. A comprehensive series of ground resonance tests was therefore undertaken to establish the vibration modes and frequencies of the tailplane and tabs. Problems were encountered in accurately simulating the tab control circuit stiffness in the laboratory, and additional tests were carried out with the tailplane fitted to an N24 production aircraft. The results obtained were used to correct the laboratory test results where necessary. These resonance tests showed that the tab frequencies for use in the flutter analysis would be within the range 19-26 Hz.

Available unsteady aerodynamic data were considered inadequate for the reliable prediction of the forces acting on a control surface fitted with trailing edge T strips. To obtain better data, a two-dimensional wind tunnel model was prepared by modifying a section of Nomad tailplane and fitting it with 47 pressure tappings enabling the chordwise pressure distribution to be measured. During wind tunnel testing, shakers oscillated the tabs at various frequencies to represent the conditions prevailing during flutter, Fig. 35. Tests were carried out at tunnel speeds of 80 and 100 knots, with and without T strips. The results obtained enabled the preparation of a correction matrix to modify the theoretical pressure distributions so as to agree with measured values.

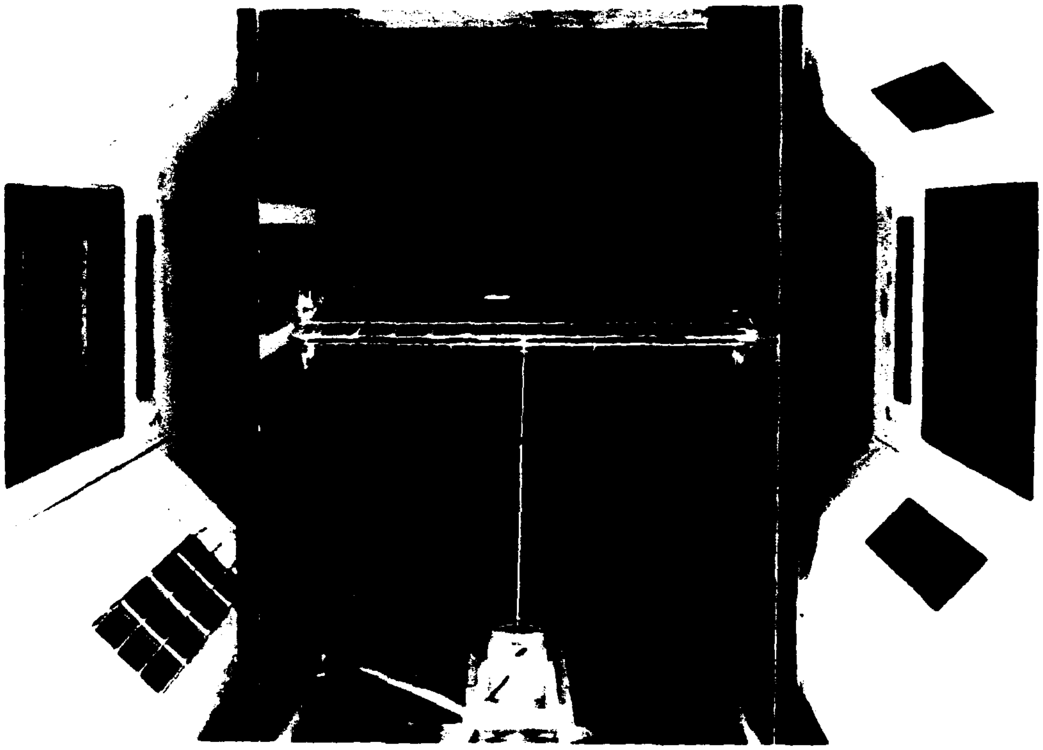


Fig. 35 Nomad tailplane under test in the ARL low speed tunnel. Trailing edge T strips were not fitted for this test

Using these ground resonance and wind tunnel test data, the theoretical analysis gave critical flutter speeds within the range 73-132 KEAS depending upon assumptions made with respect to aerodynamic and structural damping. Best estimates of the damping present, and other parameters, gave a most likely flutter speed of 103 KEAS which was in close conformity with the estimated airspeed at the time of the accident. Perhaps the most significant outcome of the theoretical analysis was that it showed the existence of flutter at frequency parameters well above the range normally considered practicable by simplified design criteria such as the Broadbent Criterion. This was the criterion used by GAF to clear the Nomad for test flights. Such criteria are empirically based and can only be relied upon when aerodynamic surfaces are conventional in the sense of past practice.

The ARL investigation was reported in the Department of Transport Technical Supplement 77-1, Report on Investigation of Tailplane Flutter. Three lessons could be learnt from this investigation. It re-affirmed the need for caution when modifying control surfaces and, certainly, the combination of full span tabs with full span trailing edge T strips represented a major modification from any of the configurations previously flown. It emphasised the unwisdom of relying on past experience when assessing the safety of unconventional configurations. Finally, it demonstrated the scale of the resources required to investigate a technically complex accident. Without scientific expertise backed by ground resonance test equipment, wind tunnel, computer hardware and software, this investigation could not have been brought to a successful conclusion.

12. FATIGUE

The fatigue of aircraft components has been of particular concern to Australia partly because aircraft utilisations tend to be high and partly because of the unusually severe load spectra applied to aircraft operating in Australian conditions. The fatigue of metal components was first recognised in the failure of railway axles in the 19th century and, later, in the failure of automotive components. Recognition of fatigue as an aeronautical problem seems to have been unduly belated and was only fully accepted, albeit with some hesitation, towards the end of World War 2. During that war, some twenty Vickers Wellington bombers crashed in the UK alone because their wings failed in fatigue. These aircraft had a mean flying life of 320 hours with a minimum as low as 180 hours, a graphic illustration of the urgency of the problem. Yet the report on these accidents was not drafted until July 1947 and published in 1949 as ARC Reports and Memoranda No. 2300, The Investigation of Aircraft Accidents involving Airframe Failure. Even then, R & M 2300 speaks of fatigue-like fractures as if reluctant to accept reality.

This reluctance was not shared by ARL where the fatigue failure of a propeller blade from Lockeed Electra VH-UZO had been correctly identified as early as May 1943. Cracking originated at a forging defect in the blade surface and progressed to failure in 3580 hours as against the normal replacement life of 6000 hours. However, research into fatigue at ARL received its major impetus from the crash of Stinson A2W VH-UYY. On 31 January 1945, VH-UYY was operating a scheduled service from Melbourne to Broken Hill when its port wing failed in flight in gusty conditions and it crashed at Redesdale, Vic. with the loss of ten lives. An examination of the separated port outer wing disclosed a defective weld in the main spar lower boom. A fatigue crack had initiated at a cavity formed by incomplete penetration of the weld metal and had propagated around the tubular steel boom until failure occurred at 13,760 hours; see S & M Note 134.

A second fatigue related fatal accident occurred a few months later when Bristol Beaufort A9-587 crashed on 2 July 1945 after shedding a propeller blade in flight. A detailed metallurgical examination of the failed blade showed that the fatigue crack initiated in a region where copper had been precipitated along the grain boundaries. Preferential corrosion of these boundaries had produced a stress raiser to initiate a fatigue crack which propagated to failure in 290 hours. After numerous tests, S & M Note 142 concluded that the grain boundary precipitation resulted from incorrect heat treatment of the original ingot.

These early examples serve to illustrate the main features of fatigue. The crack originates at a stress concentration resulting from poor detail design or produced by a manufacturing defect. Frequently these features appear minor, even trivial, but their effect is not; particularly when they exist in a region subject to a high alternating stress. The fracture surface is intergranular and markedly free from the plastic deformation normally associated with overload failure. Stages in crack progression are usually indicated by visible striation markings and tear bands. It follows that fatigue is relatively simple, lacking the aerodynamic and structural complexities of flutter for example, but the end result can be equally catastrophic.

The point is illustrated by Vickers Viscount VH-RMQ which crashed near Port Hedland, WA on 31 December 1968 after its starboard wing failed in flight. None of the 26 occupants survived. An examination of the starboard wing showed that failure resulted

from a fatigue crack in the main spar lower boom at station 143, i.e. at the No. 3 engine nacelle. At the time of the accident, the aircraft had made 8090 flights since new spar booms were fitted as against the prescribed boom replacement life of 11,400 flights so that, clearly, something had gone wrong somewhere.

A microscopic examination of the fracture surface at station 143 showed that fatigue had started within a bushed hole in the rear horizontal flange of the boom, Fig. 36. The bushed holes in the boom were fitted with interference fit steel bushes designed to improve the fatigue life of the boom but, as Applied Report 66 concluded, there was a substantial misfit between the bush and the bore of the hole at station 143. The hole had been anodised and was originally of the correct dimensions. However, the bush had been flared approximately 0.006 in. oversize at its leading edge before insertion. As a result, the hole had been broached oversize during the insertion of the bush with a consequent loss of interference between bush and hole. Following this accident, the manufacturer reduced the boom replacement life to 7000 flights but, in Australia, all Viscount 700 series aircraft were withdrawn from service.

Fig. 36 **The fatigue fracture in the main spar lower boom at station 143. Cracking originated in the bushed hole at left**

GAF Nomad A18-401 crashed at Mallala, SA on 12 March 1990 after the tailplane failed in flight. The pilot was killed in the accident. An examination of the tailplane wreckage revealed several fatigue cracks radiating at 45° from a flanged inspection hole cut in the front spar web at the aircraft centreline. One of these cracks had progressed to failure. Fatigue cracks at this location were first detected in 1981 and regular inspections were introduced to ensure the continuing airworthiness of the aircraft. These procedures had not saved A18-401 from falling victim to a known problem.

Prior to its last inspection, the tailplane had flown 414 hours with an additional 148 hours of ground running time. Since then, it had accumulated a further 19 hours of flight time and 34 hours of ground running time. The ground running time was associated with engine performance tests, mostly with one engine at high power, gust locks removed and with the control column forward to hold the tailplane against its static stops. Following the accident, ARL analysed the data obtained from an instrumented tailplane fitted to a Nomad during engine ground running tests. The results obtained showed that, for the above conditions, the rate of fatigue crack propagation was about two thousand times greater than in normal flight which explains why the accident occurred. The lesson to be learnt from this accident is that airworthiness procedures are based on the assumption that an aeroplane will be used as an aeroplane. When it is used for some other purpose, and A18-401 was used largely as an engine test bed, then airworthiness procedures are automatically invalidated.

The fatigue failure of mechanical components is not normally catastrophic but, as always, there are exceptions as exemplified by Westland Wessex helicopter N7-215. On 11 December 1983, N7-215 was in normal cruising flight above the waters of Bass Strait when the pilot noted an unusual vibration at an 'intermediate' frequency. As the vibration worsened, speed and altitude were reduced to 60 KIAS and 100 ft AMSL respectively while course was set for the Ninety Mile Beach. Approximately five minutes after the onset of vibration, a loud bang was heard emanating from a point above the cabin roof. Control was lost, the aircraft rolled violently to port and somersaulted into the sea.

Salvage operations were successful in that most of the aircraft, with the exception of the tail rotor and tail boom, was recovered and transported to East Sale where it was examined by ARL officers. This examination showed that the power input pinion had cracked through from the outer rim to the central hole, and the gear ring had broken away from its splined boss, Fig. 37. This separated the engine from the main transmission gearbox thus depriving the main and tail rotors of all power. With the abrupt loss of load, the free power turbine oversped and shed all its blades.

Fig. 37 The power input pinion from N7-215 as recovered compared with a new pinion. Note that the radial crack passes completely through the gear ring

Metallurgical examination of the power input pinion showed that the crack through the rim was a fatigue crack which had existed for a considerable time. The crack developed from a non-metallic inclusion, produced during manufacture, which intersected the surface at the base of one tooth. Initially, the crack grew slowly but accelerated once it penetrated the carburised surface. After passing completely through the gear ring, the crack changed direction from radial to circumferential, proceeding rapidly around the boss until final failure occurred. The onset of unusual vibration probably corresponded to the transition from the initial stages of fatigue cracking to the stage of rapid propagation. With the ever widening crack upsetting the correct meshing of the gears, noise and vibration amplitudes progressively increased although the frequency remained constant.

Control of the main rotor is achieved through the swashplate and doughnut assembly - the star assembly. This assembly is supported by three control servos at a radial spacing of 120°, two forward to port and starboard, and one on the aircraft centreline behind the gearbox. Loss of any one of these servos means that the main rotor is uncontrollable, i.e. the system is non-redundant. When the gear ring separated, it was ejected through the gearbox casing dislodging the port servo which fell to the floor of the transmission bay. Lacking adequate support, the swashplate tilted forward and to port with a consequent tilting of the lift vector in the same direction; hence the violent roll to port and nose down pitch manoeuvre experienced by the aircraft.

The location of the forward servos relative to the power input pinion was poor. In the event of pinion failure, its gear ring could only be projected tangentially to the main crown wheel to dislodge either the port or starboard servo. Whether it went to port or starboard would depend on which was driving which at the instant of failure. The difference would seem to be of academic interest only; it would hardly matter to the pilot whether the inevitable loss of control was manifested by a violent roll to port or to starboard.

The fatigue failure of seemingly minor components can be equally catastrophic. On 28 April 1977, the pilot of F-111C A8-136 noted a hot oil warning light for the starboard engine. Engine lubricating oil passes through a heat exchanger in which fuel is used as the coolant. Normal procedure for a hot oil light is to select afterburner; the increased fuel flow will then cool the oil and the light should go out. On this occasion, selection of A/B 1 on the starboard engine, with the port engine throttled back, caused the light to go out only to come on again when power was reduced. The process was repeated three times with increasing afterburner required on each occasion. On the final occasion, A/B 4 was required and it apparently never occurred to the pilot that something might be wrong and that the starboard engine should be shut down, The entire sequence occupied about ten minutes with the aircraft accelerating to about 540 knots with the successive applications of afterburner.

As the aircraft passed over Armidale, NSW at approximately 5500 ft altitude, eyewitnesses noted nothing obviously amiss. However, about six miles further on, the pilot reported an explosion within the aircraft, then a fire warning light, followed by a complete loss of control. Eyewitnesses observed the aircraft streaming fuel from the forward fuselage followed by a small fire which spread rapidly until it enveloped the entire aircraft aft of the wing leading edge. As the aircraft commenced rolling uncontrollably to starboard, both crew members ejected successfully.

The wreckage of the aircraft was found in three distinct groups. The first group, six miles from Armidale, consisted of panels from the port saddle tank and pieces of the fin leading edge. The port saddle tank is an integral fuel tank which sits above the port engine in the rear fuselage and it was quickly obvious that some of its panels had struck and dislodged the fin leading edge. The panels showed no sign of fire or explosion indicating that the tank had ruptured through being overpressurised. The second group, seven miles further on, consisted of the crew module and various fuselage items which had separated during the ejection sequence. The third group comprised the impact crater, containing the main body of the aircraft, surrounded by sundry debris which had been thrown clear during ground impact.

An inspection of the starboard engine revealed that the duct which bleeds air from the 16th compressor stage had failed by separating from its bolting flange, Fig. 38. As originally designed, the duct was butt welded to the flange with an external fillet weld. Because of problems with the welds cracking in service, the junction had been reinforced by the later addition of an internal weld. Detailed metallurgical examination showed that the welds had failed in fatigue. Cracking began in a region where incomplete fusion had produced a weld-parent metal lap. This formed a re-entrant surface in which oxide material was trapped and from which crack growth had initiated.

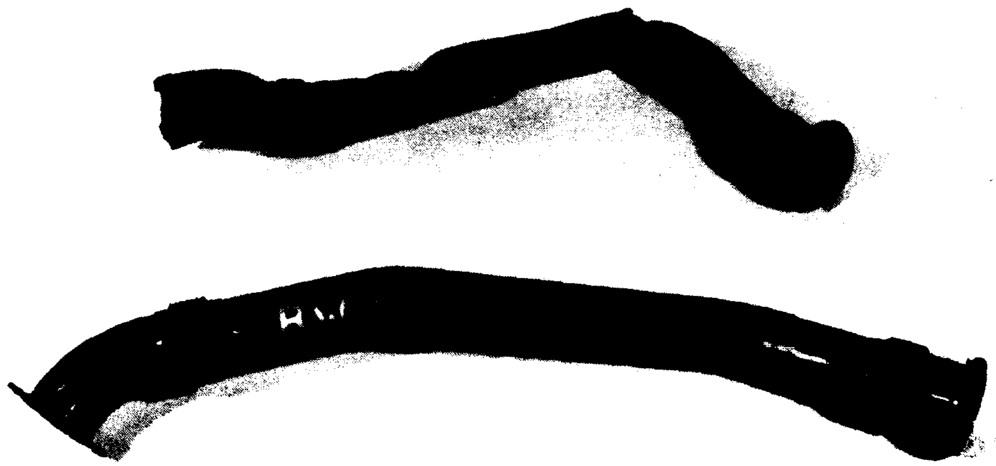


Fig. 38 Hot air duct from A8-136 as recovered compared with a new duct

Pressurisation of the duct to 250 psi during the engine start-stop cycle is the main source of alternating stresses in the welds. An examination of the engine log books showed that the starboard engine of A8-136 had experienced at least 100 such cycles during 186 hours of operation since the reinforcement weld was made. However, standard procedure is to start the starboard engine first, then to use bleed air from this engine to start the port engine. This procedure doubled the number of major load cycles applied to the duct of the starboard engine to something over 200, compared with the figure of approximately 300 estimated from fatigue crack progression marks.

When the duct failed, hot air was directed on the engine bay heat shield. This situation was reproduced in the ARL combustion test facility where it was demonstrated that, under these conditions, the heat shield had a life of approximately one minute. Once the heat shield failed, the hot air impinged on the saddle tank wall, the fuel system overpressurised, resulting in multiple failures in the fuel system. This probably was the source of the explosion reported by the pilot and explains why fuel was observed emanating from the forward fuselage. It also explains why the fire spread so rapidly.

The loss of A8-136 was not an isolated event. On 25 October 1978, another F-111C crew were forced to eject when A8-141 suffered an in-flight fire off the coast of New Zealand. Again, the problem was traced to failure of the 16th stage bleed air duct so that a solution to the problem was becoming urgent. The manufacturer's cure was to extend the neck of the bolting flange, thus moving the problem about one quarter of an inch without entirely solving it. The ARL solution was to redesign the bolting flange by machining, from a solid block of heat-resistant nickel alloy, a modified flange incorporating a tubular

extension which embraced the end of the duct. This eliminated the butt weld and the risk of hot tearing.

The RAAF suffered its first fatigue induced wing failure when Macchi A7-076 crashed into the sea off Williamtown, NSW on 22 November 1990; Applied Technical Memorandum 35. The pilot was killed in the accident. From an investigator's point of view, this accident had two interesting aspects. The accident was witnessed by other pilots in the vicinity who reported that the starboard wing had failed while A7-076 was recovering from an air combat manoeuvre. On recovery of the wreckage, it was clear that it was the port wing which had failed; a good example of the need to treat eyewitness evidence with caution. The wreckage was recovered from beneath 400 ft of salt water on 27 December 1990. Despite the long immersion, the fatigue fracture surface at station 917 was remarkably free from corrosion thanks to the low oxygen content of water at this depth. It is never easy to salvage wreckage from deep water but, as this accident demonstrated, perseverance can be rewarding.

A detailed metallurgical examination of the fracture surface, Fig. 39, showed that cracking had initiated at a fastener hole drilled in the front flange of the spar lower boom at the outboard end of the wing attachment fitting. The tip of the drill had been allowed to break through the back face of the flange without being carried right through and the drill had been stopped in the hole leaving sharp edged notches at the base of the hole. The result was high stress concentration factors in a region of high local stress. These features were not confined to the single fastener hole at station 917, most of the fastener holes over the fatigue critical section exhibited similar features. Collectively, these features indicated poor quality control and a lack of understanding of requirements.

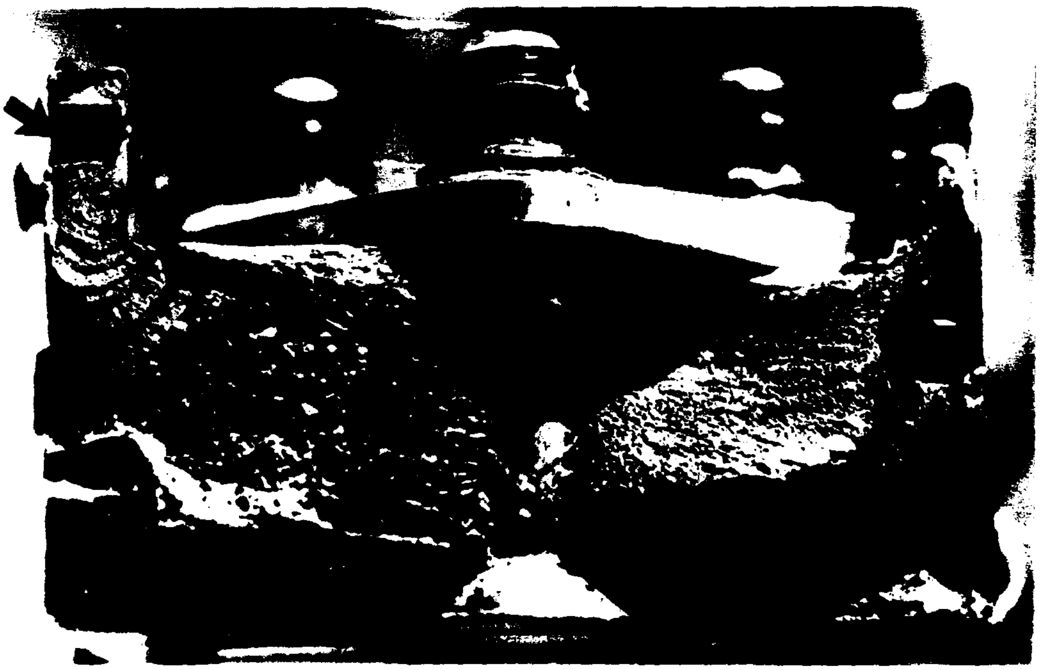


Fig. 39 **Fracture surface across the main spar lower boom of A7-076 looking inboard. Fatigue initiated at the fastener hole at top left (arrow). The outboard end of the steel wing attachment fitting is indicated (W)**

13. HELICOPTERS

To the aircraft accident investigator, the main problem with helicopters is that, after breaking up in the air or hitting the ground, the main rotor then proceeds to cut up the pieces. Thus damage caused by the main blade strikes is added to the general chaos resulting from engine disintegration, structural failure, ground impact and fire. The first helicopter accident investigated by ARL demonstrated the problem in a small way and indicated the shape of thing to come.

When Sud Djinn VH-INP crashed at Gatton, Queensland on 21 May 1958, it was, or should have been, a fairly minor accident. While hovering at a height of 6 - 8 ft, the aircraft suddenly crashed to the ground probably through pilot error; Applied Technical Memorandum 9. As a result of the ground impact, the pylon collapsed allowing one main blade ejector to strike the ground. (The Djinn main rotor was driven by tip ejectors expelling air bled from the engine compressor.) The ejector promptly separated to be flung 654 ft. Torque reaction failed the main rotor shaft and the rotor went 36 ft in the opposite direction striking and destroying the rudder in the process. The aircraft was written off as beyond economical repair.

On 29 January 1969, Bell UH-1B Iroquois A2-719 crashed near Captain's Flat, NSW, both occupants being killed, Fig. 40. From the reports of eyewitnesses and from the layout of the wreckage, it was evident that the aircraft had broken up in the air. On 2 April 1969, UH-1B Iroquois A2-386 also crashed in the Captain's Flat area, the accident site being within two miles of the previous accident. Again preliminary reports indicated that in-flight structural break-up had occurred and again both occupants of the aircraft were killed.

Fig. 40 Main wreckage of A2-719 with the failed mast at centre right

When the first accident occurred, A2-719 was engaged upon an instrument flight exercise with two experienced pilots aboard, one flying the aircraft and the other acting as safety pilot. The weather was fine with unrestricted visibility and a light easterly wind. In the second accident, A2-386 was participating in a line astern formation flying exercise with another aircraft which was leading. The exercise included a series of climbing or descending turns to port and starboard. The pilot was new to this exercise as was his companion, who was not participating as a pilot, but merely observing the manoeuvres. Neither aircraft transmitted a radio call indicating an emergency or any departure from routine. There were no indications of any in-flight fire or explosion in either case. As a result of these two accidents, the RAAF grounded the Iroquois aircraft until the cause of the accidents had been established.

The two-bladed main rotor of the Iroquois is of the teetering hinge type, i.e. the two blades are fixed to a rigid yoke which hinges about a trunnion attached to the top of the drive shaft, also termed the mast. The mast consists of a steel tube of approximately 3.5 in. outside diameter and 0.25 in. wall thickness. It combines the functions of driving the main rotor and supporting the weight of the fuselage. It also acts as a static stop limiting the angular travel of the main rotor yoke.

The wreckage of each aircraft was examined at the crash site and again after removal to RAAF Fairbairn where the two aircraft were largely re-assembled side-by-side. These examinations showed that, in each case, violent mast bumping had occurred, i.e. the static stops on the main rotor yoke had struck the mast two or three times with sufficient force to deform the annular cross-section, Fig. 41. The mast then failed primarily in bending, with some tensile and torsional loading applied. Following mast failure, the main rotor separated and rolled to port relative to the aircraft. During this period the main rotor blades, still rotating, struck the aircraft four or five times inflicting extensive damage on the cabin, engine bay, port undercarriage skid, tail boom and elevator.

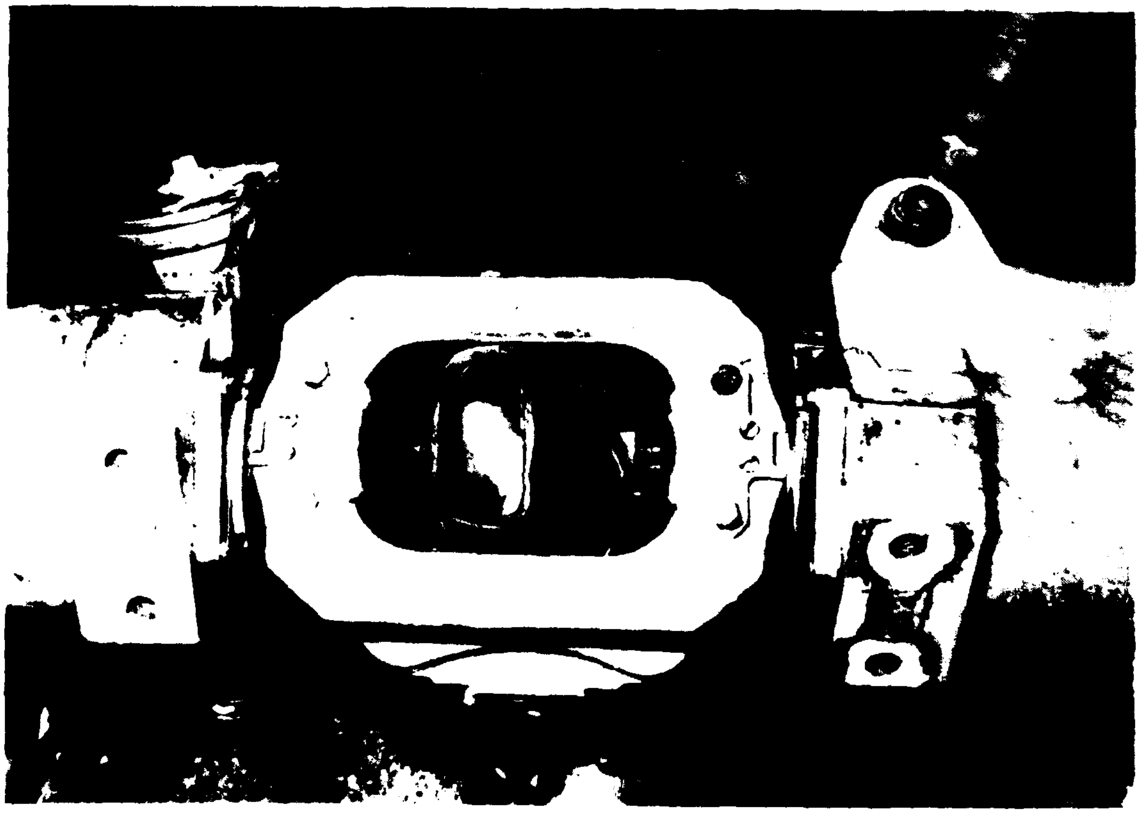


Fig. 41 Main rotor yoke of A2-719 showing the deformed and broken mast

The tail rotor is mounted vertically on the port side of the fin and is of the pusher type, i.e. its thrust is directed inboard towards the fin from port to starboard. In each case, the tail rotor blades had repeatedly contacted the side of the fin with ever-increasing force before rebounding to the limit provided by the static stops on the tail rotor yoke. Ultimately, the fin was severed, the blades failed, and the tail rotor hub was severely damaged. Finally, the tail boom failed as a result of the damage inflicted by the main blade strikes, Fig. 42, and the tail unit, or what remained of it, separated from the aircraft. Fire broke out on ground impact and largely destroyed the engine, pylon and main gearbox. As may be imagined, re-assembling the wreckage was no easy task.

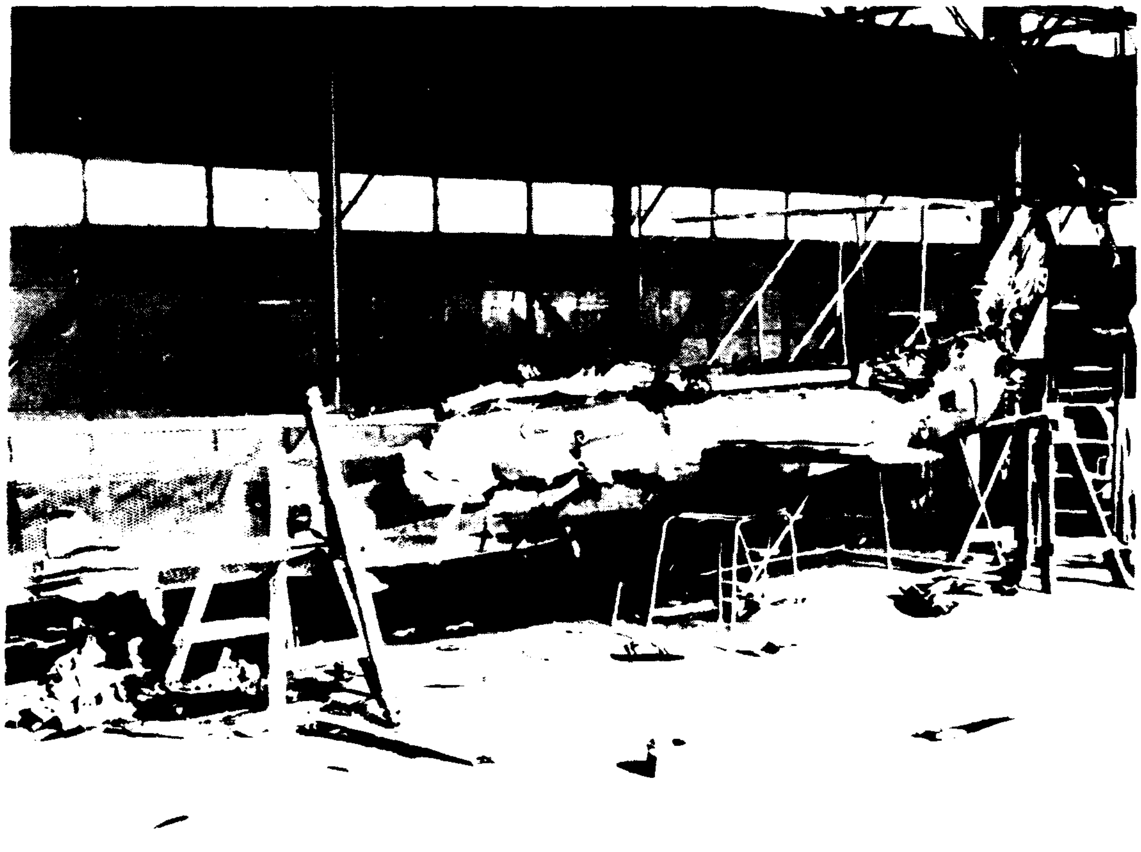


Fig. 42 **A2-719 at an early stage of re-assembly. The tail boom was severed forward of the elevator by a single main blade strike as indicated by the single impact damage to the tail rotor drive shaft**

Following re-assembly, the similarities between the two accidents were strikingly obvious. This led Applied Note 5 to conclude 'The two accidents were closely similar and resulted from a common cause. In the accident sequence, violent mast bumping produced severe deformation of the mast which then failed in bending. The main rotor then separated striking the cabin, port skid, tail boom and elevator. During this sequence, both tail rotor blades contacted the fin, leading to failure of the fin structure, and the tail boom separated from the aircraft.

A rigorous examination of the wreckage of both aircraft failed to find any indication of pre-crash effects which could have contributed to the accidents. Similarly there is no evidence to suggest that the primary cause of the accidents was a sudden catastrophic

failure in the engineering of the aircraft. Accordingly, it is concluded that the accidents resulted from violent mast bumping, but the reason for this could not be established'.

This investigation was assisted by two senior accident investigators from the US Army and three experienced engineers from the manufacturer. They fully supported, indeed encouraged, the ARL conclusion. One US Colonel remarked that he had seen it all before, many times, and what else could be expected when inexperienced pilots lost control during instrument or formation flying exercises.

In achieving this comfortable consensus, three odd facts were noted but failed to receive the attention they deserved.

a. On A2-386, the tail rotor pitch control cables were in a position appropriate to full left pedal when severed by the main blade strikes whereas, in A2-719, the cables were much closer to the neutral position.

b. There were pronounced cable grip marks on the tail rotor drive shaft of A2-386 but none on the shaft of A2-719; see Fig 42.

c. As shown in Fig. 43, the drive shaft tunnel cover of A2-386 carried a series of cable flailing marks. There were no similar marks on the tunnel cover of A2-719.

It was to be 12 years before the significance of these three facts became apparent.

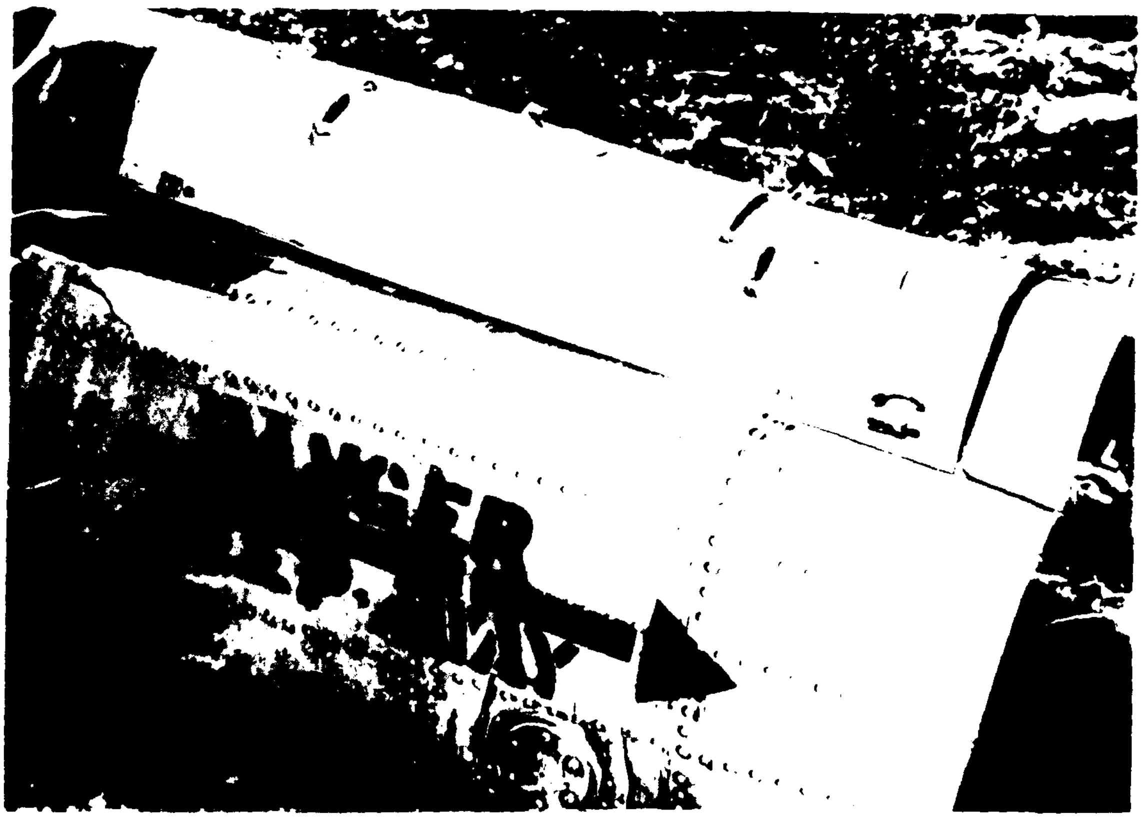


Fig. 43 Transverse holes in the drive shaft tunnel cover of A2-386 made by a flailing pitch control cable

Bell UH-1B Iroquois A2-1023 crashed at Williamtown, NSW on 19 August 1981. Many eyewitnesses observed the aircraft approaching the airfield in straight and level flight at 1500 ft altitude when, without warning, it broke up in the air. Both the main rotor and tail rotor were observed to separate from the aircraft and the general consensus of eyewitness opinion was that tail rotor separation preceded main rotor separation. The main body of the aircraft fell inverted into a swamp which effectively prevented any outbreak of fire. There were no survivors from the three crew aboard.

During examination, the main features of the wreckage began to look disturbingly familiar; violent mast bumping followed by mast failure with the main rotor repeatedly striking the aircraft as it passed down the port side. The familiar pattern was repeated by the tail rotor which had continued to strike the tail fin throughout 17-18 revolutions until one blade failed and the resultant out of balance forces tore the tail rotor away from the 90° gearbox. There were minor differences of course; the main rotor blades had not contacted the tail boom and the fin had not failed. Significantly, the tail rotor pitch control servo was in a position appropriate to full left pedal when recovered and there were pronounced cable grip marks on the tail rotor drive shaft, Fig. 44, with cable flailing marks on the tunnel cover. More significantly, the pilot was highly experienced and there was no suggestion of any loss of control preceding break-up.

Fig. 44 **Inside the tail rotor drive shaft tunnel of A2-1023 when opened after the accident. Note the short length of severed cable, the uncoupled turnbuckle, the cable grip marks on No.4 drive shaft and the extensive flailing damage to the tunnel cover**

The Iroquois achieves directional control by varying the pitch of the tail rotor blades. From the pilot's pedals, a pushrod system carries loads via a hydraulic servo to a quadrant plate located in the forward section of the tail boom. The purpose of the quadrant is to transfer loads from the pushrod system to a cable system. Pulleys and fairleads take the cables aft, past a 42° gearbox, to a 90° gearbox mounted on top of the tail fin. This is a closed loop system with the cables terminating in a length of chain which drives a sprocket to alter the pitch of the tail rotor blades. In the UH-1B, the cables run parallel to, and on either side of, the tail rotor drive shaft. Cable shields are provided adjacent to each shaft coupling. Each cable has a turnbuckle forward of the 42° gearbox for adjusting cable tension. Both the drive shaft and cables are enclosed in a tunnel which can be opened for inspection.

The cable system had failed in eight separate places and all of the failures were different. To produce eight failures in a single closed loop system is difficult; to explain those failures is more difficult. Nevertheless, they had to be explained since, in that explanation, lay the cause of the accident. The explanation is best understood by referring to the system diagram. The sequence was initiated when the starboard cable slipped off the quadrant plate and lost tension in consequence. The slack cable was now vibrating through a large amplitude as evidenced by cable slap marks on the tunnel cover and by the highly polished face of the cable shields.

Eventually, it jumped over a cable shield to be picked up by one of the bolts securing the Marman clamp of the tail rotor No. 4 drive shaft forward coupling. Shaft rotation pulled the starboard cable hard against the adjacent fairlead until the cable failed primarily in overload bending; failure 1 of Fig. 45.

With one end still jammed under the bolt head, the cable continued to be wrapped around the drive shaft pulling the quadrant and sprocket to a position appropriate to full left pedal. This abrupt application of full left pedal destabilised the tail rotor to the extent that its blades started to contact the tail fin. With no further movement possible, the starboard cable then failed in overload tension near a pulley within the fin; failure 2 Fig. 46. This allowed the starboard turnbuckle to be pulled forward and under the drive shaft where it uncoupled; failure 3 of Fig. 46. As the port cable moved forwards, it was severed by the repeated impacts of the flailing end of the starboard cable; failure 4 of Fig. 46. Immediately aft of this failure, the port cable was damaged by the impact of the flailing turnbuckle which also cut a slot in the tunnel cover, Fig. 44, and departed from the aircraft when the jagged edges of the slot severed the starboard cable; failure 5 of Fig. 47.

As the tail rotor separated from the fin, the rear section of the port cable was pulled aft and was in this position when it was severed by the single impact of a tail rotor blade; failure 6 of Fig. 47. The chain then failed in lateral bending; failure 7 of Fig. 47. During these later phases, the front section of the port cable was picked up by the drive shaft which, once again, pulled the quadrant to a position appropriate to full left pedal. It remained in this position until it failed on ground impact; failure 8. When recovered, the starboard cable was in five pieces, the port cable in three, the chain in two, and the quadrant had broken up.

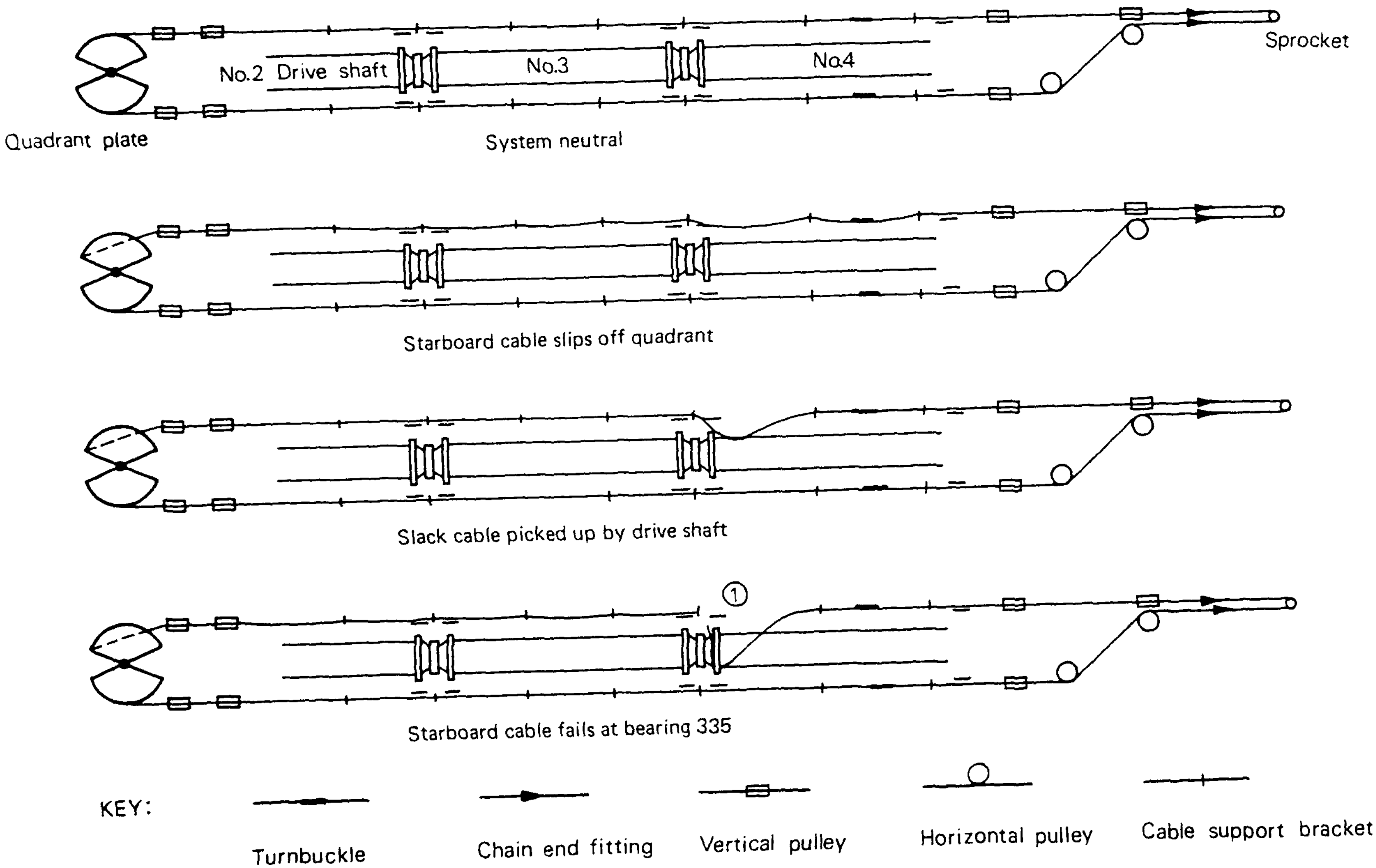


Fig. 45 Postulated accident sequence - tail rotor cable system

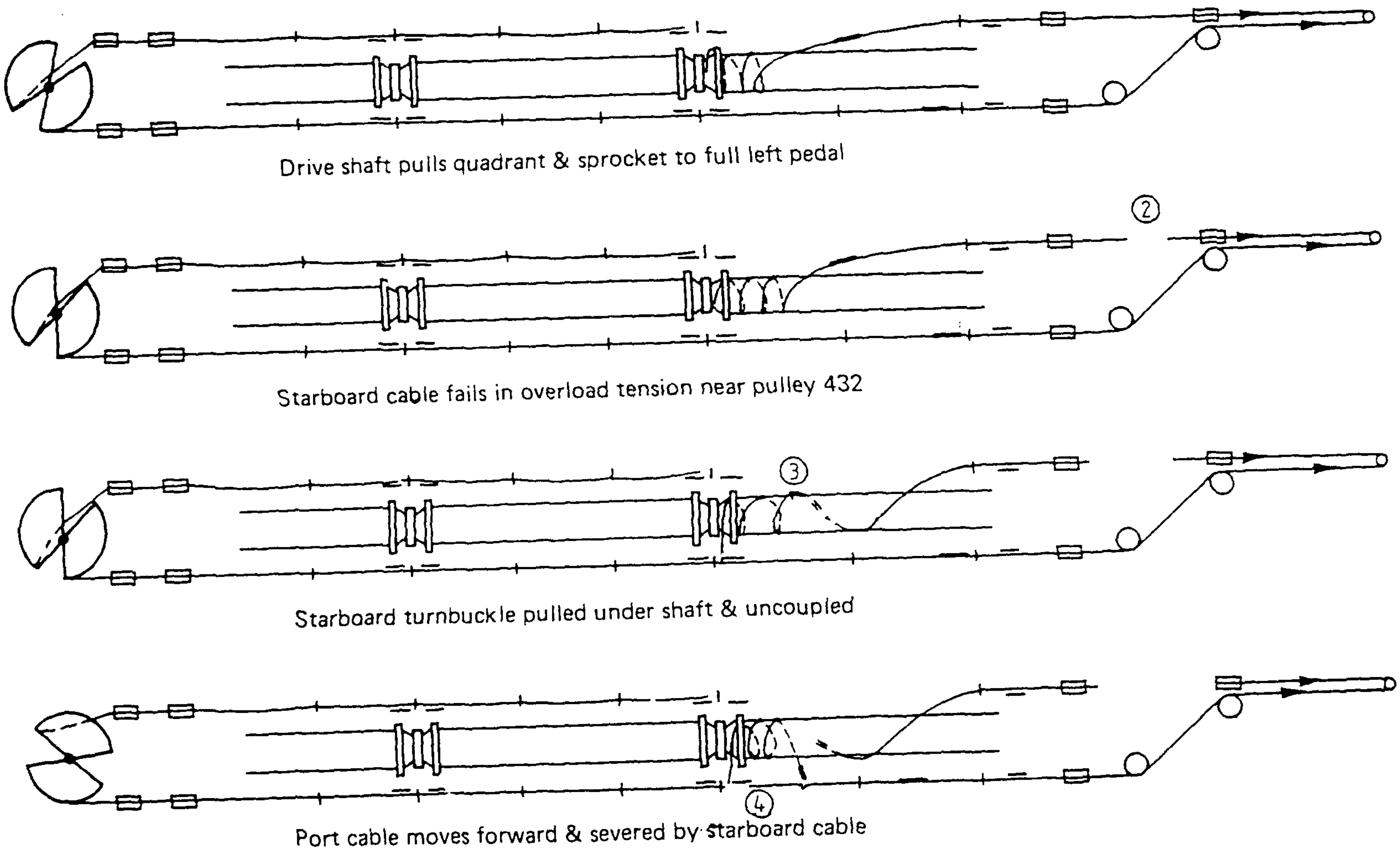
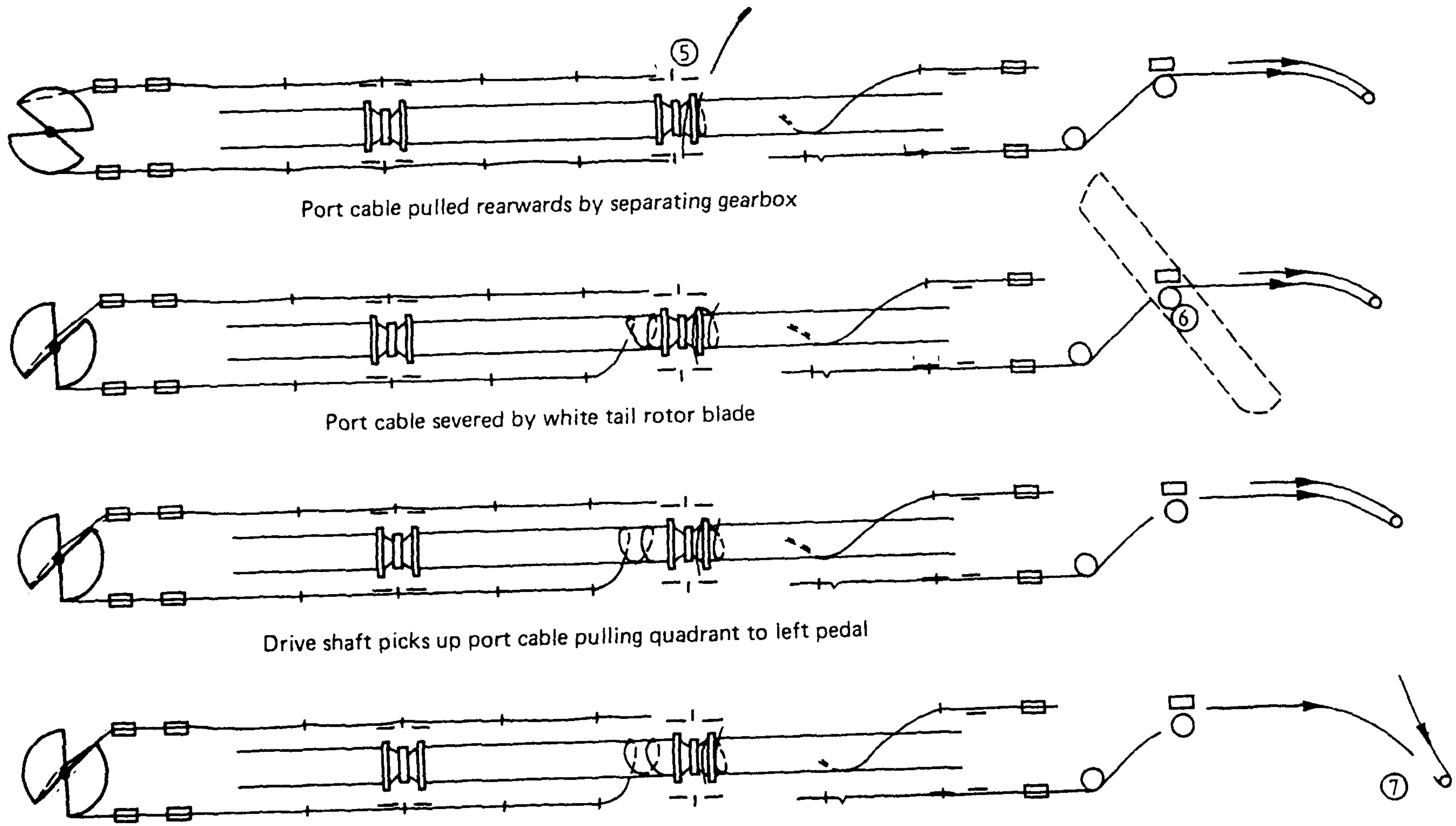


Fig. 46 Further stages in the failure of the tail rotor cable system



Port cable pulled rearwards by separating gearbox

Port cable severed by white tail rotor blade

Drive shaft picks up port cable pulling quadrant to left pedal

Upper fairlead bush pulls out and chain fails in bending

Fig. 47 Final stages in the cable system failure

The accident sequence was now clear. A slack cable was simulated in the laboratory, Fig. 48, by allowing a correctly tensioned cable to slip off the quadrant. Vibration tests on the slack cable demonstrated that it would quickly jump over the cable shield and, inevitably, come into contact with rivet heads on the drive shaft, Fig. 49. The friction of this contact would pull the cable into a position where it would be picked up by a coupling bolt, Fig. 50. In consequence, there would be an abrupt application of full left pedal, the tail rotor blades would contact the fin, the aircraft would yaw wildly and violent mast bumping would result. The question was, why did the starboard cable slip off the quadrant?

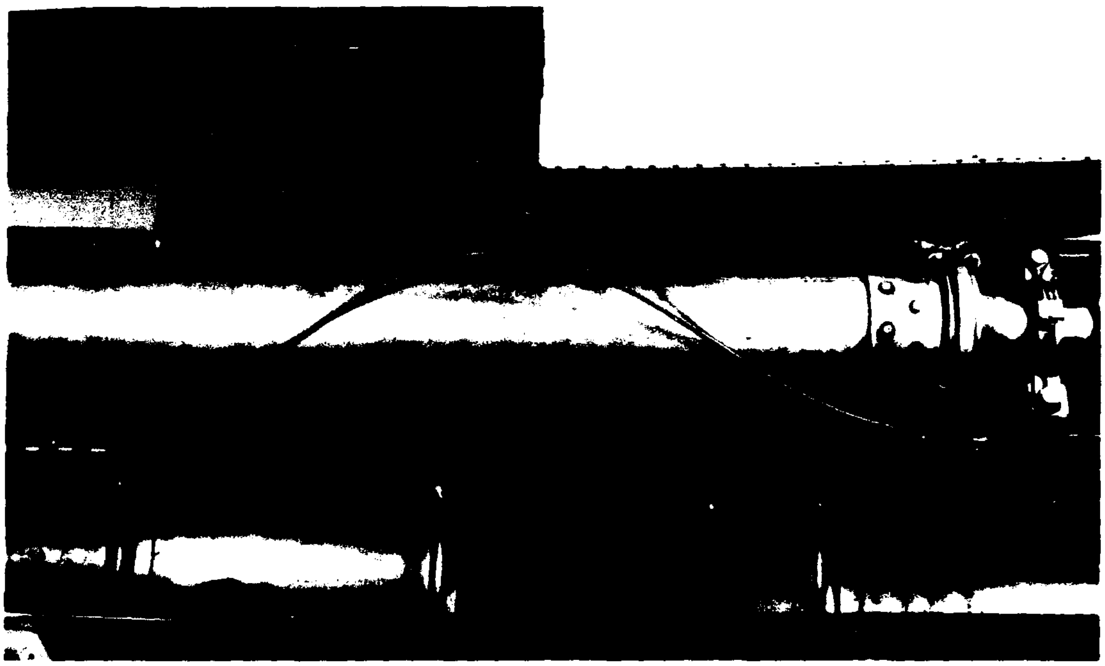


Fig. 48 **Laboratory simulation of slack starboard cable**

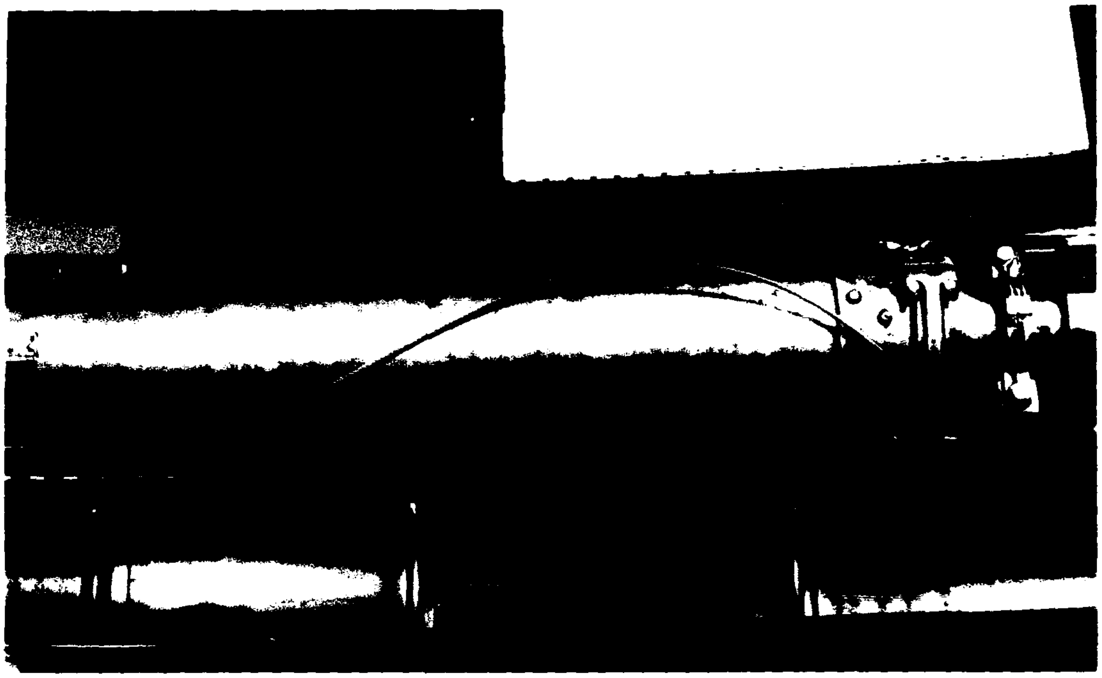


Fig. 49 **The cable has jumped over the cable shield to be in contact with rivet heads on No. 4 drive shaft**

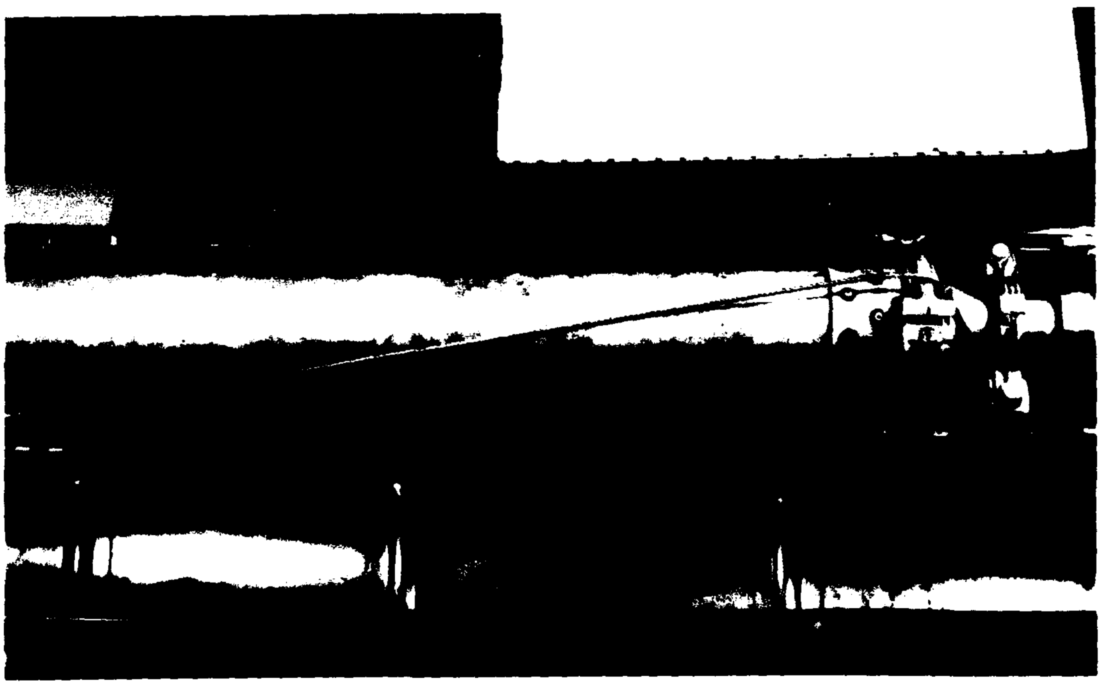


Fig. 50 **The cable has been picked up by one of the Marman clamp coupling bolts**

Cable and pulley systems have been used in aircraft since the very beginning of powered flight. Early aviators quickly learnt that cables tend to stretch in service and, with the reduction in cable tension, will slip off pulleys unless restrained by keeper pins. An inspection of the wreckage showed that the quadrant keeper pins were not fitted to A2-1023. Microscopic examination showed that the pins had originally been fitted but had been removed at some time before the accident and not replaced. Accordingly, Structures Report 388 concluded that a maintenance error was the primary cause of the accident.

The report also concluded that, while the earlier accident to A2-719 had been correctly diagnosed, the accident to A2-386 had probably resulted from cable pick-up by the tail rotor drive shaft. This was one of the few occasions where ARL managed to get it wrong and the error cost three lives. There is some irony in the fact that, without the help of overseas "experts", ARL might have managed to get it right first time around. To locate vital cables in close proximity to rotating shafts is poor design. While manufacturer's representatives ridiculed the possibility of cable pick-up by the drive shaft, it is significant that in later versions of the Iroquois, the cables are routed through the tail boom and not through the drive shaft tunnel.

Another Iroquois accident is of interest if only because it illustrates the frustration sometimes encountered in aircraft accident investigation. When flying above dense rain forest in the vicinity of Marlborough, Queensland on 30 October 1981, UH-IH Iroquois A2-380 suffered a loss of directional control and the pilot elected to land in a small clearing. After passing through trees, the aircraft touched down on the rim of a concealed shallow gully. It then rolled down the slope and came to rest inverted at the bottom of the gully. The aircraft was largely destroyed in the intense fire which followed. An examination of the tail rotor blades, and of the trees through which they passed, indicated that the tail rotor had been virtually stationary at touchdown.

The tail rotor drive system was checked for continuity to the extent possible. This showed that, apart from No. 1 drive shaft, the system was intact until tree impact and confirmed that rotation had ceased before ground impact. The No. 1 drive shaft was destroyed by fire. All steel components from the rear coupling of this shaft were subsequently recovered including the four coupling bolts which were found within the stainless steel drive shaft tunnel. Despite an intensive sifting of the ashes, only two bolts from the forward coupling were recovered. One of these bolts was straight, the other showed a distinctive compound bend. Laboratory tests showed that this combination could be reproduced by removing the two bolts from one side of a Marman clamp and then loading the two remaining bolts by applying radial and axial loads to the clamp. Thus it appeared that two forward coupling bolts had failed, the Marman clamp had opened allowing the spring loaded curvic coupling to disengage cleanly without damage to its gear teeth.

The recovered forward bolts had been machined from a medium carbon, low alloy steel of similar composition to AMS 6322, the alloy steel specified for their manufacture. Metallurgical examination showed the bolts to be in an annealed condition rather than in the specified hardened and tempered condition. While it was possible that the bolts had been softened in the post-impact fire, ARL metallurgists were of the opinion that the bolts had not been heat treated during manufacture. In the annealed condition, the bolts have a substantially lower tensile strength and fatigue endurance than specified.

Structures Technical Memorandum 346 hypothesised that all four bolts originally fitted to the forward coupling of the No. 1 drive shaft were from the same production batch and all were in the soft condition. One of the bolts failed in service thus overloading the remaining bolt on the same side of the Marman clamp. Eventually this bolt also failed allowing the coupling to disengage the drive to the tail rotor. However attractive, this hypothesis could not be proved because the suspect bolts were never recovered.

A final helicopter accident worthy of mention is that involving Agusta A109C serial M38-02 of the Royal Malaysian Air Force on 19 September 1990. One of two similar aircraft purchased by the Malaysian Government for VIP transport duties, M38-02 was shipped to Port Klang where it was assembled and prepared for its delivery flight to RMAF Simpang. After take-off and initial climb out, the aircraft was put into cruise-climb configuration until, at about 1000 ft altitude and 110 KIAS, the pilot felt a sudden jolt in the aircraft. Subsequent control checks revealed that neither pilot nor co-pilot was able to obtain yaw control through operation of their respective rudder pedals. However, the aircraft was controllable provided airspeed was maintained above 50 KIAS. Realising that the landing would be hazardous, the pilot elected to remain airborne for some three hours to burn off excess fuel. At 2205 hrs, an approach was made into Subang which offered better facilities than the planned destination. During the final stage of the approach, yaw control was lost as speed diminished and the aircraft landed heavily on the runway. All occupants evacuated the aircraft safely but M38-02 was damaged beyond economical repair, Fig. 51.

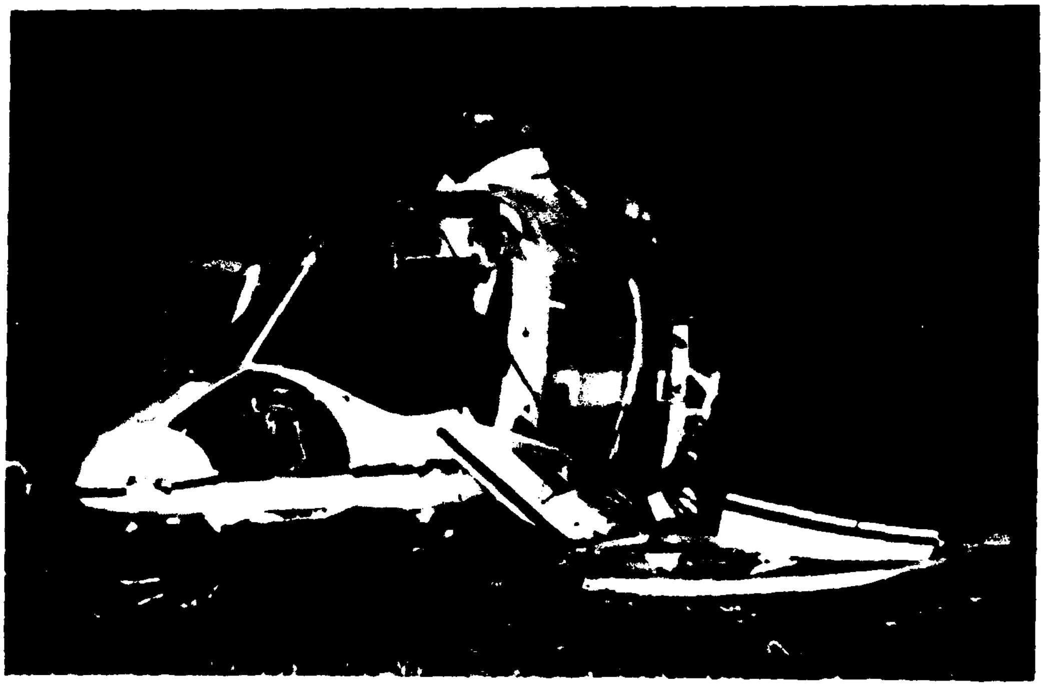


Fig. 51 Wreckage of Agusta A109C M38-02

Following an initial investigation into the cause of the accident, the Malaysian Government requested Australian assistance and two officers from ARL travelled to Malaysia to participate in the investigation. They quickly perceived that the pylon assembly had rotated in flight forcing the forward coupling of the tail rotor drive shaft sideways and rearwards so that it jammed between the compressor drive drum and the stainless steel firewall. The coupling then failed, Fig. 52, depriving the tail rotor of all power, and yaw control was lost.

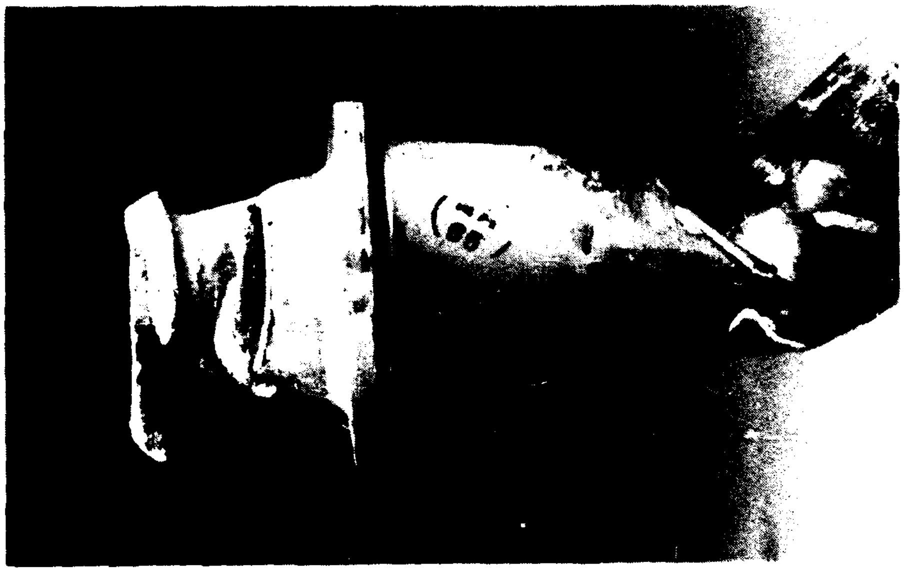


Fig. 52 **The failed drive shaft coupling from M38-02. Note the broken lugs at right caused by contact with the compressor drive drum, the cut in the end fitting made by the firewall, and the ground impact buckling of the shaft at left**

The pylon assembly consists of the main gearbox, mast, main rotor, control servos and various accessories. It is attached to the fuselage by two forward struts and two sway braces extending laterally to either side. All supports are fitted with flexible ball joints at both ends. This design leaves the pylon relatively free to rotate about its attachment fittings and an anti-torque beam is provided to prevent any such rotation. The beam runs laterally across the base of the pylon and is bolted to two deck fittings attached to the fuselage structure to port and starboard.

An examination of the wreckage showed that the starboard deck fitting had failed in flight by cracking circumferentially around its two bolting bosses. This failure allowed the pylon assembly to rotate while reacting the main rotor torque. Microscopic examination of the deck fitting revealed an extremely coarse grain structure around the base of the bosses where the section had been heavily reduced by forging. Fine continuous precipitate networks existed along the grain boundaries increasing the material's susceptibility to brittle fracture. These features suggested that temperature control during forging had been poor leading to excessive grain growth with consequent degradation in

mechanical properties. Applied Technical Memorandum 34 concluded that the starboard deck fitting was cracked prior to the flight and failed with the application of a suitable flight load.

The report also noted that the port deck fitting suffered from the same defects and was very close to complete failure when the aircraft landed. Had it failed in flight, there would have been little constraint to further pylon rotation. Such rotation would have failed the pylon supports, the pylon would have separated and the resulting accident would have been non-survivable. To continue flying an aircraft after a serious in-flight failure, is not a good idea.

14. HUMAN FACTORS

Back in the days of the AAIC, pilot error was regarded as an adequate explanation for the cause of an aircraft accident but, today, the term is seen as superficial, frequently glossing over the underlying causes. Those causes need to be identified and understood if repetition is to be avoided and that, surely, is the purpose of accident investigation. Many of the accidents mentioned in the previous sections contain an element of pilot error. Inevitably, pilots will make mistakes but that is no reason for stacking the cards against them. This section looks at a few accidents investigated by ARL where the cards were unreasonably stacked. The first of these involved the Bristol Sycamore helicopter XN449.

On 3 September 1962, XN449 took off from Nowra for a period of dual instruction on sloping ground landings. While hovering at 15-20 ft above the selected landing area, the pilot experienced great difficulty in maintaining directional control in the strong and gusty wind. The aircraft tended to turn to port, i.e. against the thrust generated by the pusher type tail rotor mounted on the starboard side of the tail fin. The pilot decided to cancel the exercise, applied power and began a transition into forward flight with the port turning tendency still apparent. At a height of about 50 ft, all three tail rotor blades failed and separated. The aircraft promptly developed an uncontrollable left hand spin, crashed on sloping ground, rolled over and caught fire, Fig. 53. Both occupants evacuated the aircraft safely.

Fig. 53 **The remains of XN449 liberally doused with foam. The tail boom, minus the tail rotor, is towards the camera**

An inspection of the tail rotor blades showed that all blades had contacted the rear fuselage as indicated by rivet score marks and paint smears on their inboard faces. At least two of the blades contacted the fuselage more than once. With the continuing succession of contacts, there was progressive deterioration in the structural integrity of the blades to the extent that they ultimately failed. The inspection also revealed chordwise scratch markings across the outboard face of each blade near the tip, Fig. 54. These scratches could only have been made by contact with some external object and, since the scratches were equidistant from the tip, the tail rotor must have been intact and rotating normally at the time.

Fig. 54 **The three tail rotor blades from XN449 showing chordwise scratches on their outboard faces**

ARL therefore concluded that failure of the tail rotor blades was initiated by their contact with an external object, probably trees, which destabilised the rotor to the extent that the blades then contacted the rear fuselage. As evidenced by the minimal damage shown in Fig. 54, the blades made only light contact with the trees. Certainly the pilot should not have allowed his tail rotor to contact trees but, equally certainly, it should not have had such a catastrophic effect. Aircraft design should have some reasonable tolerance to pilot error.

Aircraft flight simulators are essential to train pilots to fly complex and expensive aircraft safely. Initial training and continued practice in correct emergency procedures can often only be done in a simulator and it is imperative that it provide the most accurate simulation possible. Where completely accurate simulation is not possible, both instructors and trainees should be aware of the nature and magnitude of any disparities. Only in this way can appropriate allowances be made. Any failure to adhere to these principles is a good way of stacking the cards.

On 10 February 1960, CAC Sabre A94-924 crashed near Williamtown, NSW, Fig 55, after its engine failed at a height of 600 ft. A strip examination of the engine disclosed fatigue failures in the gear teeth of the high pressure fuel pump drive. Four weeks later, Sabre A94-926 suffered a similar fate when it crashed near Williamtown on 7 March 1960 following engine failure at 200 ft, Fig. 56. On this occasion, the engine failure resulted when a distorted and displaced cooling air duct allowed the turbine disc to overheat. The disquieting feature of these two accidents was that in neither case had the pilot attempted to eject; while the canopy had been jettisoned, the ejection seat gun had not fired.

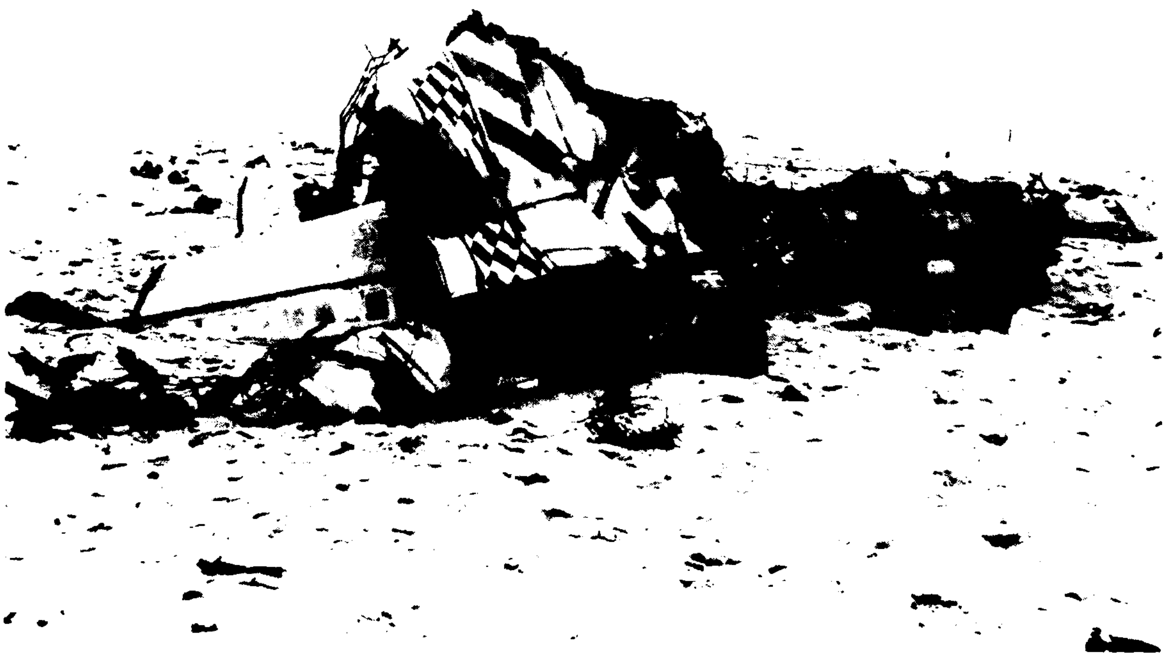


Fig. 55 A94-924 on the beach near Williamtown

Fig. 56 A94-926 ended its days in a paddock

When a Sabre canopy is jettisoned, it initially slides rearwards on its rails before separating. The jettison procedure requires the pilot to bend well forward, with his head down, then to grasp one of the jettison levers below the front of the arm rests of his seat and then, with his head still down, to pull up the lever thus firing the canopy jettison cartridge. The procedure is inherently difficult and it is easier to grasp a lever, and to commence pulling it upwards, before bending forward. The pilots of both A94-924 and A94-926 had sustained helmet damage and head injuries through being struck by the canopy during its initial rearwards movement. These injuries were sufficiently incapacitating to prevent completion of the ejection procedure. As a result of these two accidents, all Sabre pilots were briefed on the necessity of keeping the head well down during canopy jettison, and not to attempt short cuts when a lack of height made the ejection urgent.

On 12 April 1960 when at a height of 300 ft, the pilot of Sabre A94-937 made a radio call to report that he had a cockpit fire and was ejecting. The aircraft subsequently crashed on a bush covered hillside near Williamtown, Fig. 57. Again the ejection attempt was unsuccessful and, again, the familiar pattern of canopy jettison, helmet damage and head injuries was evident. An examination of the wreckage disclosed no evidence of cockpit fire but, clearly, something was badly wrong.

Fig. 57 A94-937 was the last of three fatal Sabre accidents during a nine week period

Sabre pilots practised their emergency procedures on a Sabre simulator at Williamtown. An examination of this simulator showed that its canopy jettison levers did not simulate cartridge firing until they had been moved through 97 - 99° of travel. A survey of Sabre pilots revealed that 42% believed that the levers had to be pulled through their full travel of 120° before the cartridge fired. Another 45% thought the levers could be pulled through 70° before this occurred while the remainder thought the relevant travel was about 60°. Many pilots expressed the opinion that they would have started to move a lever upward before adopting the awkward bent forward, head down position, believing that they could do so in complete safety. This was a disastrously wrong impression since measurements on actual aircraft showed that cartridge firing occurred after as little as 12° and generally between 20° and 30°. The false impression created by the simulator was reinforced by the ambiguity of the Technical Information Manual which could be interpreted to mean that the cartridge would not fire until a lever had been pulled fully up.

With three expensive aircraft destroyed and three valuable pilots dead, this was a bad nine week period for the RAAF. In earlier days, the cause of the accidents would have been variously described but the reason for the unsuccessful ejections would have been covered by the all-embracing term of pilot error. Such a conclusion would have missed the point entirely.

NZ Aerospace CT-4 Airtrainer A19-028 crashed at Oakey, Queensland on 16 August 1979 killing the crew of two. From an inspection of the ground impact markings, it was determined that the aircraft had been diving at 25° with 10° of starboard bank when initial ground impact occurred. Following this impact, the aircraft bounced and finally came to rest during a second heavy impact. A thorough examination of the wreckage disclosed no evidence of any pre-crash defect, all control surfaces and control runs were intact at ground impact, and it was concluded that the aircraft flew into the ground because of the pilot's inattention to his flight path. Despite the fact that the cockpit structure survived relatively intact, Fig. 58, this accident was considered non-survivable because of the large vertical accelerations experienced.

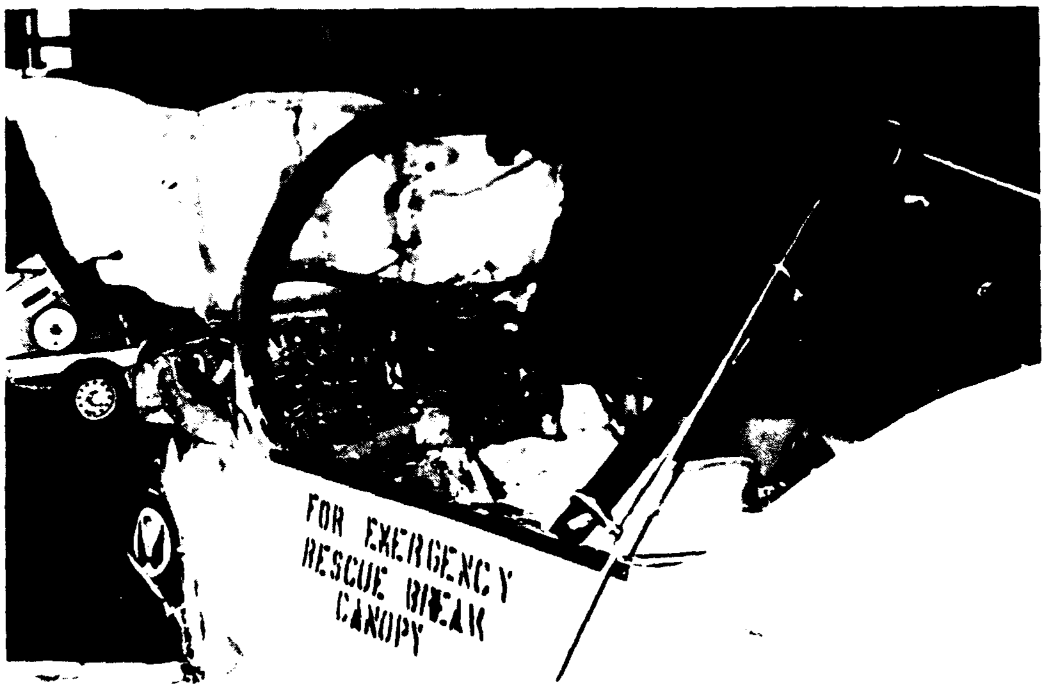


Fig. 58 Cockpit structure of A19-028 after the accident. Note the impact damage to the instrument panel and the missing windscreen

However, both occupants received fatal injuries when they were thrown through the windscreen. This should not have happened. A close examination of their safety harnesses revealed that these had been fitted properly, inertia reels had locked correctly, and the harnesses had not failed through overload. Instead, the quick release buckles had distorted during the initial impact and then unlocked during the subsequent rebound allowing the occupants to be ejected during the second heavy impact. This accident accelerated ARL research into pilot restraint systems with particular attention being given to improved designs of quick release buckles.

Another way of stacking the cards is to impose an excessive work load on the pilot and the work load is never higher than when making a night landing aboard an aircraft carrier at sea. The point is illustrated by the accident to Grumman Tracker N12-153608 which crashed while attempting a night landing aboard HMAS *Melbourne* on 10 February 1975. The investigation of this accident was a novel experience for ARL; the request for assistance was received from the RAN more than 12 months after the accident, there was

no wreckage to examine, and the investigation was, perforce, based solely on written statements by eyewitnesses.

Tracker N12-153608 was catapulted from the carrier at 2200 hours on 9 February 1975 to carry out an anti-submarine warfare close support task. The night was unusually dark with no visible horizon so that approximately three hours of the flight were spent in Instrument Meteorological Conditions (IMC). At 0323 hours the following morning, the aircraft attempted a routine landing using the mirror landing system as an approach aid. In the days preceding the accident, the mirror setting had been changed from an approach slope of 4° to 4.5° but the pilot had not been informed of this. In consequence, the approach was slightly high and fast, the aircraft failed to pick up an arrester wire, an event known as a "bolter", and it subsequently crashed into the sea approximately ten seconds later. All four crew members managed to escape from the sinking aircraft and were rescued uninjured.

On receiving a bolter call from the Landing Safety Officer, standard procedure was for the pilot to open the throttles to full power and to establish a positive pitch up attitude, then to select undercarriage up while the Tactical Co-ordinator (Tacco) in the right hand seat raised the flaps from full to $^2/_3$ down. One difficulty with this procedure was the need to monitor the engine instruments closely to avoid exceeding the maximum permissible boost pressure of 57 inches Hg. Since the Tracker engines were not fitted with automatic overboost protection devices, this requirement imposed an additional work load on the pilot at a critical time. According to both the pilot and Tacco, full power was achieved with the vertical gyro indicator (VGI) showing a positive pitch up attitude of 5° as the aircraft left the flight deck. The RAN Board of Inquiry accepted this evidence and concluded that the failure of the aircraft to climb away successfully resulted from an inadvertent selection of zero flap by the Tacco.

Subsequent flight trials showed that, under the accident conditions of 87 KIAS and 22,000 lb aircraft weight, the Tracker had such a large performance reserve that it could climb away at any positive pitch angle from zero to 7.5° regardless of flap position. Faced with this evidence, the Board of Inquiry withdrew its earlier findings and requested further investigation.

ARL began its investigation by noting that the Tracker had provision for two modes of flap operation. In the normal retraction mode, an orifice in the hydraulic circuit restricted the flow to limit the rate of flap retraction. The size of the orifice was apparently selected to provide a flap retraction rate that optimised the initial climb performance of the aircraft. That is, the flap retraction rate was matched to the usual acceleration. Selection of zero flap would therefore result in better aircraft performance than the selection of $^2/_3$ flap as required by standard operating procedures. This was confirmed by flight trials. In the fast retraction mode, which required the aircraft to be supported by the undercarriage, the orifice was bypassed to allow fast retraction.

Having eliminated flap operation as the cause of the accident, only two possible alternatives could be postulated, viz. loss of power and incorrect pitch attitude. Both the pilot and Tacco stated that full power was applied and maintained. Some external witnesses were less certain but none suggested that the sound of the engines had varied considerably to indicate a substantial loss of power. Again, flight trials showed a large power reserve such that satisfactory climb performance could still be achieved with boost pressures reducing rapidly to 42 inches Hg. There was a consistent thread running

through the statements by external witnesses that the aircraft attitude was flatter than normal with estimates ranging from level to slightly nose down, e.g. 'definitely not a climbing attitude at any stage'. Even the Tacco and one of the crewmen in the rear of the aircraft sensed that the attitude was abnormally flat. Yet both the pilot and Tacco were adamant that the VGI was registering 5° nose up.

To human factors experts at ARL, this accident had all the hallmarks of the "dark night take-off accident". This term is used to describe an accident which results from the failure to establish a positive rate of climb following take-off in conditions which deprive the pilot of external visual cues. In this situation, the pilot senses a push in the back but is unable to distinguish between the forces resulting from linear acceleration and gravity. Hence, horizontal acceleration is easily misinterpreted as a pitch up attitude (somatogravic illusion). Under these conditions, it is vital for the pilot to monitor his flight instruments closely, particularly with respect to pitch attitude and rate of climb. This is all very well but the instruments must be read correctly. If the pilot is suffering from disorientation, there is a strong tendency to see what ought to be there rather than what is actually there.

Spatial disorientation implies a false perception of attitude and motion. The four conditions which lead to its onset were all present in the case in question, viz:

a. a state of anxiety or mental arousal prevalent for some minutes prior to the event,

b. control of the aircraft had involved a motor task of one or both hands,

c. immediately prior to the event, the pilot had been distracted from the immediate task of controlling the aircraft attitude,

d. horizontal acceleration had rotated the apparent gravity vector.

Certainly in the period preceding the accident, the pilot was highly aroused on the mirror approach and had been manually controlling the aircraft; the bolter situation, bolter call and undercarriage actions provided a distraction from the attitude control task and the horizontal velocity was changing.

Applied Report 78 concluded that the most probable cause of the accident was that the pilot was affected by unrecognised disorientation associated with somatogravic illusion and flew the aircraft into the sea. Factors thought to have contributed were:

a. the exceptionally dark night,

b. the pilot's unawareness of the change of settings to the mirror landing aid,

c. the pilot's lack of any previous bolter experience,

d. the need to monitor engine instruments instead of the VGI as the aircraft was rotated.

The VGI readings stated to have been present during the overshoot probably were incorrectly perceived because of the visual disturbances and mental confusion characteristically associated with disorientation episodes.

Finally, a word about collisions. Over the years, ARL has been involved in the investigation of a number of in-flight collisions and that between DH Dove VH-WST and Piper Twin Comanche VH-WWB over Bankstown, NSW on 13 March 1974 is a typical example. These two aircraft flew slowly converging courses for over one minute before they collided wing tip to wing tip and broke up in flight. None of the four occupants survived. The investigations usually centre around two questions; why did the pilots fail to see each other in time to avoid the collision and, if appropriate, why did they fail to eject successfully? These questions can frequently be answered provided the exact collision geometry is established and this is ARL's function. In performing this function, it is necessary to seek the unique solution which satisfies all of the in-flight damage. Any solution which discards some of this damage as intractable, cannot be right.

A case in point is provided by two Douglas Skyhawks of the RAN which collided in flight at Nowra, NSW on 17 July 1975. The contact was gentle, inflicting only minor damage on the two aircraft, to the extent that the pilot of N13-155051 was able to land without undue difficulty. However, N13-155055 crashed and the pilot was killed. Once ARL established the exact collision geometry, it became clear that the latter pilot must have suffered incapacitating head injuries during the collision and his failure to land, or eject successfully, was thus explained. The point is illustrated more fully in the following description of the collision between two F/A-18 aircraft near Tindal, NT on 2 August 1990.

The two aircraft were practising a simulated pairs intercept. In this exercise, two aircraft track an electronically generated radar return presented on their head-up displays. The aircraft manoeuvre until one achieves parameters which satisfy missile launch requirements. Missile launch is simulated and the launching aircraft continues to provide radar illumination of the simulated target throughout the computed missile flight time. Aircraft manoeuvres are quite violent throughout the interception and a high degree of teamwork is required.

Head-up displays are recorded on videotape during the exercise. An inspection of the tape from A21-29 showed that the aircraft was pulling about 3.3g in a 90° banked turn to starboard, Mach 0.86, altitude 32,000 ft, when it collided with A21-42. During the collision, A21-29 lost most of its port wing outboard of the wing fold, Fig. 59, and a 2 ft section of its port tailplane was removed. Control was retained and the aircraft landed successfully. The pilot of A21-42 was killed in the accident; his aircraft crashed and was totally destroyed.

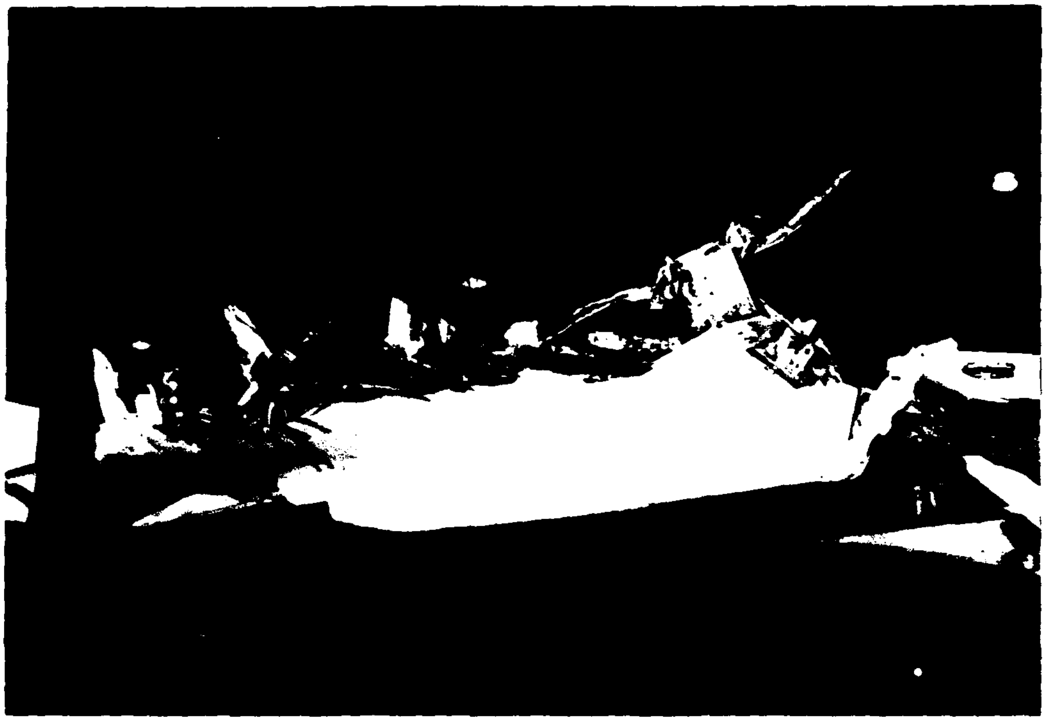


Fig. 59 Collision damage to the port wing of A21-29

An AIM-9 missile was mounted on the port LAU-7 wing tip launcher of A21-29. An analysis of the wreckage showed that this missile had impacted and destroyed the canopy of A21-42. In the process, the dummy warhead of the missile broke up completely and, since the canopy bow (Fig.60) was the only component in the area sufficiently stiff to generate the required impact forces, this enabled the exact collision geometry to be determined.

Fig. 60 **Canopy bow from A21-42 showing the impact damage inflicted by the dummy warhead of the port wing tip missile of A21-29**

Structures Technical Memorandum 565 was then able to postulate the collision sequence in detail as follows:

a. The forward section of the missile on the port wing of 29 impacted the windscreen of 42, Fig. 61. The seeker head, fuze and warhead separated from the missile and the windscreen disintegrated.

b. The missile motor impacted the canopy which was destroyed. The motor separated from its launcher and struck the pilot's head and the ejection seat.

c. Simultaneously, the nose of the launcher on the starboard wing of 42 contacted the port jet orifice of 29 causing the launcher to separate.

d. The nose of 29's port launcher contacted the canopy frame just above the cockpit sill and the launcher failed approximately 2 ft aft of the nose.

e. The main body of the port launcher passed beneath the cockpit sill cutting through the pilot, destroying the ejection seat and forcing the control column hard left, Fig. 62. The port tailplane of 29 was now in contact with the starboard wing of 42.

f. With 42 commencing to roll to port, the port wing of 29 moved progressively downwards to the leading edge extension, disintegrating as it entered the cockpit. Cockpit equipment was forced out of 42 through the port side of the fuselage.

g. The starboard leading edge flap separated from 42 while the port tailplane tip was removed from 29, Fig 63.

h. After 0.125 seconds, the two aircraft separated with 42 rolling and turning to port before falling into a spin.

Reconstruction of the collision geometry enabled the relative velocity vector to be established. As shown in Fig. 61, this was essentially lateral with a magnitude of only 50-55 knots. Under the circumstances, it was not surprising that the pilot of A21-42 failed to see A21-29 nor that he failed to eject.

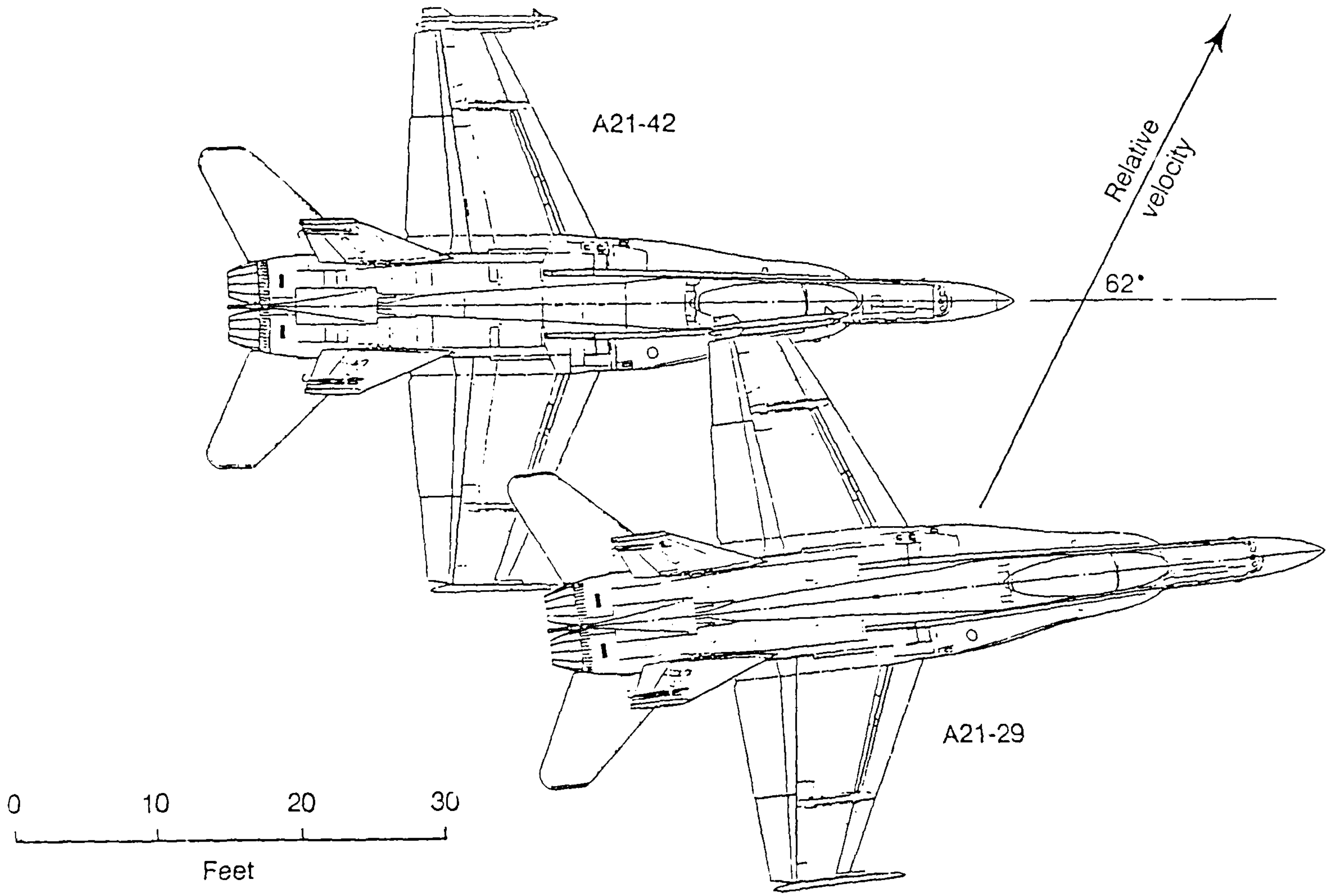


Fig. 61 $t = 0$ the two aircraft at initial contact with the port missile of A21-29 impacting the windscreen of A21-42 and the starboard launcher of A21-42 touching the port jet orifice of A21-29

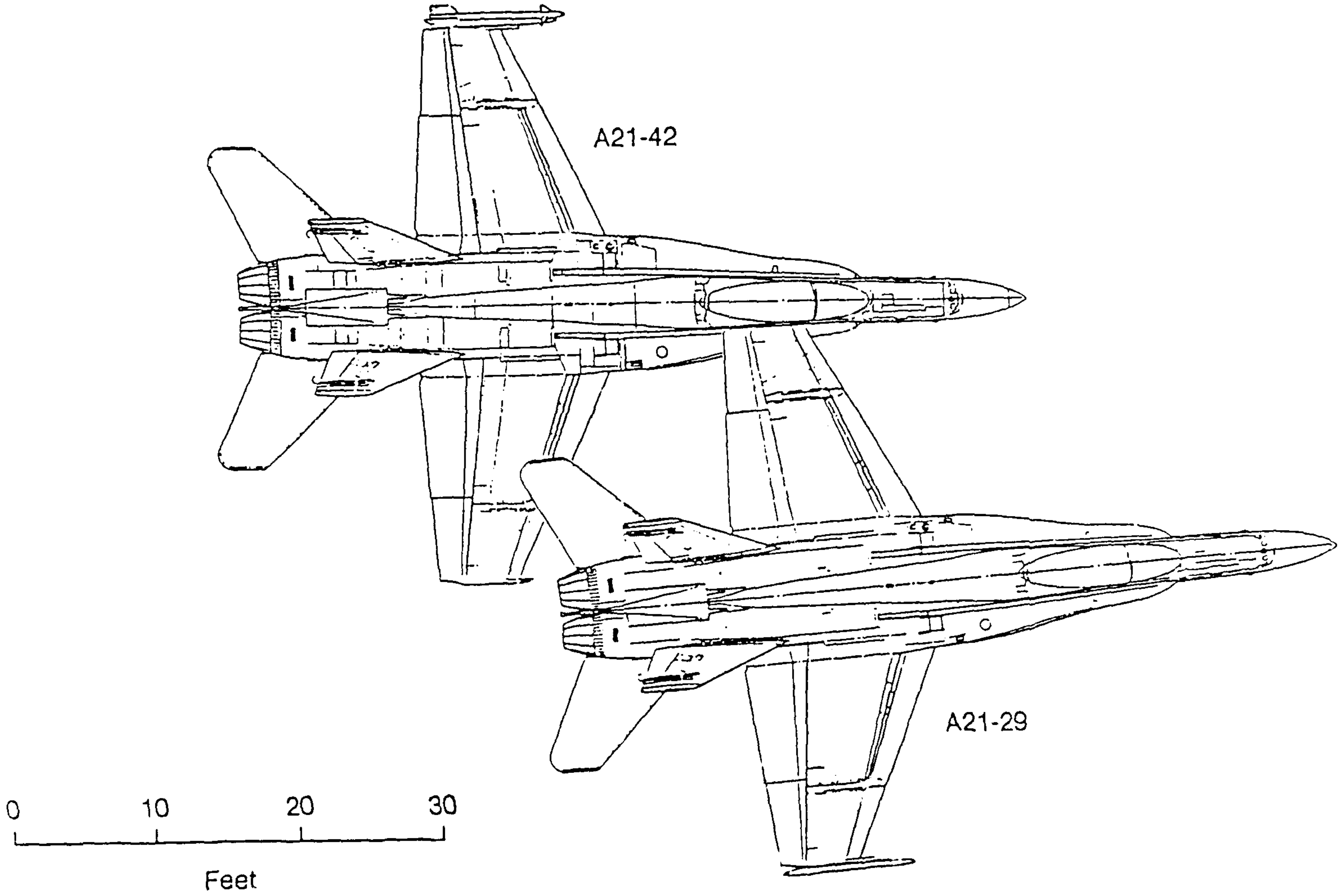


Fig. 62 *t = 0.022 sec following separation* of the missile, the port wing of A21-29 penetrates the cockpit of A21-42 while the port tailplane of A21-29 contacts the starboard wing of A21-42

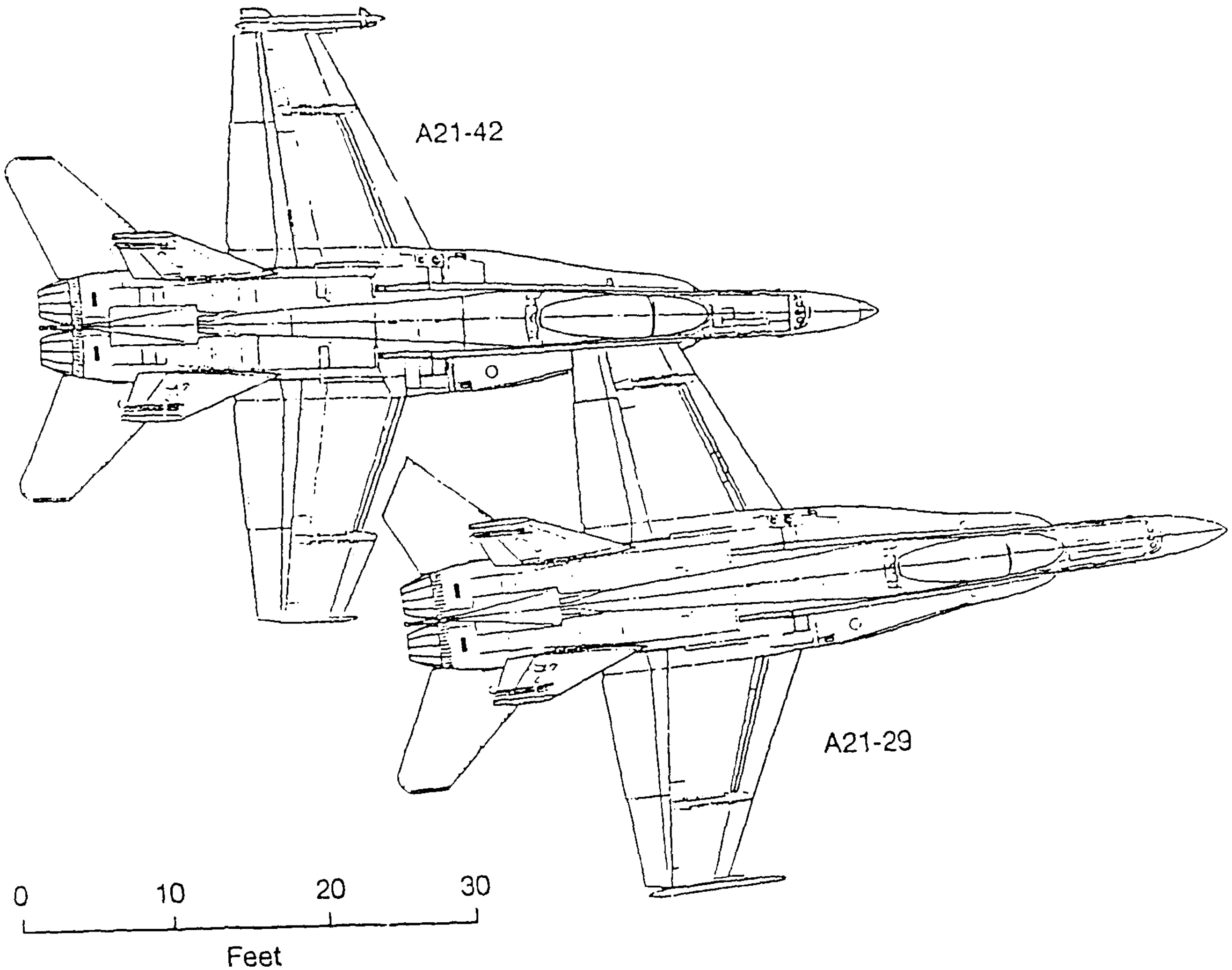


Fig. 63 t = 0.125 sec the port wing of A21-29 *continues* to penetrate the cockpit of A21-42; the port tailplane tip of A21-29 breaks off while the inboard leading edge flap separates from A21-42

15. CONCLUDING REMARKS

This report began in a rather light-hearted vein and became progressively more serious. This was not intentional; it simply reflects the trend in aircraft accidents. The accident to Maigre's balloon was innocuous, even entertaining, but there is nothing innocuous or entertaining about an accident to a modern high performance aircraft. The costs, both human and financial, are just too high.

It is often remarked that, because of the ever increasing complexity, weight and performance of aircraft, accident investigation is becoming ever more difficult. While this is undoubtedly true, some of the early accidents were quite complex, including those to the Puss Moth for example, but they didn't cost as much. High performance and complexity certainly increase the technical difficulties of accident investigation but it is cost that adds an urgency that wasn't there before.

On looking back at the early history of aircraft accident investigations in Australia, it is clear that many of these investigations were hampered by inadequate knowledge, inexperience and lack of support facilities. Technically complex accidents were, of necessity, referred to overseas authorities and the answers were often a long time in coming. This was a significant factor in the decision to create ARL. With the foundation of ARL, there was an immediate marked improvement as evidenced by the Anson wing failures. It could be argued that ARL was founded ten years too late; perhaps the trauma generated by the DH.86 accidents could have been avoided had ARL existed at the time.

ARL gathers together, within the one establishment, expertise covering the full range of the aeronautical sciences. This expertise is supported by extensive laboratory facilities, computers and associated software. These assets are backed by considerable experience, and ARL's experience with the investigation of aircraft accidents goes back virtually to its very beginning. Within Australia, ARL is unique; it is the one organisation which can approach a technically complex accident with a reasonable expectation of success.

The purpose of accident investigation is to discover the cause in order that appropriate corrective measures can be implemented in a timely manner, thus preventing any recurrence. These objectives are not always achieved and this report contains several examples where accidents went on recurring despite the best efforts of the ARL investigators. However, over the past fifty years, a remarkably high standard has been maintained which will withstand comparison with the best overseas. The important thing is to maintain continuity, to learn from past mistakes and to strive for improvement.

As these pages indicate, one lesson that has been learnt is the folly of relying on overseas experts. Frequently their expertise is less than advertised and, if they represent the aircraft manufacturer, their objectivity is suspect. Perhaps ARL's most important quality is that of professional integrity; a willingness to face facts however unpalatable.

If there is one continuing thread running through this report, it is the need to explain damage. It is always tempting to discard damage evidence that won't conform to preconceived ideas; it's not the evidence that's wrong, but the ideas. This is not a new observation.

Arrange your facts. Arrange your ideas. And if some little fact will not fit in - do not reject it, but consider it closely. Though its significance escapes you, be sure that it is significant.

Hercule Poirot - The Murder on the Links
(Agatha Christie, 1923)

Arrange your facts. Arrange your ideas. And if some little fact will not fit in - do not reject it, but consider it closely. Though its significance escapes you, be sure that it is significant.

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APPENDIX 1

CHRONOLOGICAL LIST OF ARL PUBLICATIONS ON AIRCRAFT ACCIDENT INVESTIGATION

1. T.F.C. Lawrence and H.W. Maley. "Examination of damaged wing from Wirraway aircraft. ARL S & M Report 5, February 1941.

2. H.A. Wills. "Examination of damaged Anson wings A4-5 and N1331. ARL S & M Report 6, March 1941.

3. H.A. Wills and J.B. Dance. "Examination of damaged wing from Hudson aircraft (Bairnsdale accident)". ARL S & M Report 17, December 1942.

4. C.J. Osborn. "Examination of failures in Stinson model A wing structure". ARL S & M Note 134, March 1945.

5. H.T. Greenaway. "Metallurgical examination of the airscrew of a crashed Mustang aircraft". ARL S & M Note 139, July 1945.

6. H.T. Greenway. "Failure of Curtiss electric airscrew". ARL S & M Note 142, August 1945.

7. B. Foster and F.W. David. "Statement on investigation of accident to Mustang aircraft A68-13 at Pearce W.A. on 2nd June 1950". ARL Applied Report 1, January 1951.

8. F.H. Hooke, N.B. Joyce and C.A. Patching. "Analysis of wreckage of Bristol "Freighter" aircraft". ARL S & M Report 224, August 1954. (Contains the following three Technical Memoranda as appendices).

9. F.G. Lewis. "Examination of fractured wing spar booms from a Bristol Freighter". ARL Metallurgy Technical Memorandum 154, April 1954.

10 I.J. Polmear. "Examination of rivets from Bristol Freighter No. A81/2". ARL Metallurgy Technical Memorandum 155, March 1954.

11. C.A. Patching. "An interim statement of mechanical test results related to a Bristol Freighter crash investigation". ARL S & M Technical Memorandum 36, May 1954.

12. N.B. Joyce. "Assessment of damage to Sabre aircraft A94-902". ARL S & M Technical Memorandum 48, November 1955.

13. J.D.C. Crisp. "Flight flutter tests of Jindivik Mk.II with AMPOR camera pods Mk.I". ARL S & M Note 229, June 1956.

14. J. Solvey and F.G. Lewis. "Investigation of the air accident to Jindivik A92-29". ARL Applied Report 2, November 1956.

15. J. Solvey and F.G. Lewis. "Investigation of the air accident to Jindivik A92-45". ARL Applied Report 3, December 1956.

16. J. Solvey and F.G. Lewis. "Investigation of the air accident to Jindivik A92-51". ARL Applied Report 4, February 1957.

17. F.G. Lewis. "Examination of the drive gears from a constant speed governor. (Dakota A65-112)". ARL Metallurgy Technical Memorandum 188, May 1957.

18. L.M. Bland. "Examination of the swaged end of a rudder control cable from Auster J5C aircraft VH-BTA". ARL Applied Technical Memorandum 2, October 1957.

19. W. Howard. "Accident to Wirraway A20-749". ARL Applied Technical Memorandum 5, December 1957.

20. W. Howard. "Accident to Mustang A68-123". ARL Applied Technical Memorandum 6, February 1958.

21. L.M. Bland, C.A. Patching and J. Solvey. "Investigation of the air accident to Wirraway A20-679 on 2nd April 1958". ARL Applied Report 6, June 1958.

22. F.G. Lewis and J. Solvey. "Investigation of the air accident to Djinn helicopter VH-INP on 21st May 1958". ARL Applied Technical Memorandum 9, September 1958.

23. L.M. Bland. "Investigation of engine failure in Meteor WM374 at Woomera, S.A., on May 21, 1958". ARL Applied Technical Memorandum 10, September 1958.

24. C.A. Patching and J. Solvey. "Accident to Jindivik A92-90". ARL Applied Technical Memorandum 11, October 1958.

25. D.W. Glanvill and F.G. Lewis. "Failure of a Goblin impeller. (Vampire A79-625)". ARL Metallurgy Technical Memorandum 217, April 1960.

26. J. Solvey. "The influence of simulator accuracy on flight safety". Flight Safety Foundation International Seminar 1961, Phoenix USA.

27. A.S. Bennett and C.A. Patching. "Accident to Sabre aircraft A94-360 on 1 November 1961". ARL Applied Report 29, July 1962.

28. D.W. Glanvill. "Metallurgical examination of failed and cracked propellers. (Chipmunk VH-RVG)". ARL Metallurgy Technical Memorandum 231, July 1962.

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31. D.W. Glanvill and B.C. Bishop. "Examination of components from the tail rotor assembly of Bell 47G2 helicopter VH-AHF". ARL Metallurgy Technical Memorandum 278, March 1967.

32. L.M. Bland. "Investigation of in-flight disintegration of R.A.A.F. Sabre aircraft A94-358 at Newcastle near Williamtown, N.S.W. on 16 August 1966". ARL Applied Report 61, March 1967.

33. N.T. Goldsmith. "Failure of the tail fin of a Bell 204-B helicopter VH-UTW". ARL Metallurgy Technical Memorandum 291, July 1968.

34. J.L. Kepert and C.K. Rider. "Accident to Winjeel A85-416 near Drysdale, Victoria on 3rd May 1968". ARL Applied Note 4, July 1968.

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36. F.G. Lewis, D.W. Glanvill and B.C. Bishop. "Accident to Viscount aircraft VH-RMQ - metallurgical examination of components from the wing structure". ARL Applied Report 66, August 1969.

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38. J.L. Kepert and C.A. Patching. "Accident to Iroquois helicopters A2-719 and A2-386". ARL Applied Note 5, December 1969.

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41. J.L. Kepert. "Accident to Jindivik WRE.521". ARL Applied Technical Memorandum 24, April 1971.

42. G.F. Pearce. "Examination of Avon Mk. 1 engines, serial Nos. C.A.C.13 and RR 3018, from Canberra aircraft A84-205". ARL Mechanical Engineering Technical Memorandum 334, August 1971.

43. J.L. Kepert. "The use of wreckage trajectories in aircraft accident investigation". ARL Structures Note 427, May 1976.

44. B.A.J. Clark, A. Ross, J.L. Kepert and A.A. Keeler. "Loss of RAN Tracker aircraft N12-153608 on 10 February 1975". ARL Applied Report 78, December 1977.

45. M.M. Hutchinson. "Report of ARL investigations concerned with the crash of F111C aircraft A8-136". ARL Materials Technical Memorandum 370, December 1977.

46. R.J. Callinan and J.L. Kepert. "Accident to Iroquois helicopter A2-1023". ARL Structures Report 388, January 1982.

47. R.J. Callinan and J.L. Kepert. "Accident involving TOST releases fitted to a Wessex helicopter". ARL Structures Technical Memorandum 340, May 1982.

48. J.L. Kepert. "Accident to UH-1H Iroquois A2-380". ARL Structures Technical Memorandum 346, September 1982.

49. R.J. Callinan and S.A. Barter. "Accident to Wessex helicopter N7-215". ARL Applied Technical Memorandum 31, June 1984.

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51. S.A. Barter and L.W. Hillen. "RAAF Orion aircraft A9-300 oxygen fire". ARL Applied Report 84, September 1987.

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16. ABSTRACT

Early Australian experience with the investigation of aircraft accidents is covered briefly as a prelude to the foundation of the Aeronautical Research Laboratory. With its foundation, a more scientific approach was possible. ARL was quickly involved with accident investigation, an activity which has been maintained throughout its fifty year history. This report examines ARL experiences during those fifty years with the idea of providing some useful guidelines for the next half-century.

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